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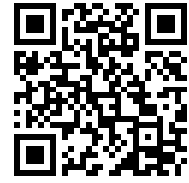

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THE DEVELOPMENT OF TUBE TRANSMITTERS BY THE TELEFUNKEN COMPANY*

By

Alexander Meissner, Dr. Ing.

(Chief Engineer, Gesellschaft für drahtlose Telegraphie (Telefunken), Berlin)

As a result of the development of thermionic amplifiers for transmitting and receiving purposes, radio engineering has been practically revolutionized during the years of the war. The basis of this development was the principle of reaction coupling, as it was given in its general form by the author in March, 1913, for receivers and transmitters.[1] The first researches carried out by the author were with the well-known Lieben tubes, which had oxide-covered cathodes and were filled with gas. It was possible, as early as June, 1913, to carry on two-way telephonic communication between Berlin and Nauen, a distance of 36 km. (22.5 miles). At that time, the transmitter was of small power (10 to 15 watts). The life of the tubes when loaded to this extent was short, since the gases in the tube were gradually used up or absorbed; nevertheless, for small powers and with plate voltages of 220, the transmitters of that time were very useful in practice and of great significance in connection with beat reception. At that time, the Fessenden beat reception method had only a theoretical value, since no practically useful and constant auxiliary oscillator was available. By using a heterodyne oscillator in combination with a detector in the receiving system, the author succeeded in producing a receiving arrangement which immediately displaced all other methods for the reception of continuous oscillations. This method of reception was first suggested by the author in March, 1913, was developed in common with Franklin and Round in the direc-

* Received by the Editor, July 2, 1921. Translated from the German by the Editor.

[1] German patent 291,604 of April 10, 1913. The first claim of this patent covers "an electric relay provided with an incandescent cathode or ionized conducting path, which is connected to a circuit capable of oscillation, both on its input (primary) and output (secondary) sides, so that any oscillations originating in the circuit will be amplified by the relay and thereafter sustained by it."

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tion of placing the tube with its reaction coupling in the receiving circuit itself, and thus permitting it to function simultaneously as a radio-frequency amplifier, as a device for the reduction of damping, as an oscillator, and also as a detector.[2]

Furthermore, the external oscillator made possible for the first time high power trans-Atlantic service between Nauen and America. At the beginning of October, 1913, the first heterodyne oscillator arrived in America. It was then used by Messrs. Pichon and van der Woude to receive signals originating from the alternator transmitter at Nauen. It was possible to receive the new high power alternators (8,000 cycles, 100 kw., with two steps of frequency doubling) on October 18, 1913, and thereafter to maintain the service. Figure 1 shows the apparatus used in Sayville for this purpose. The excellent results obtained by this new method of the producing oscillations aroused

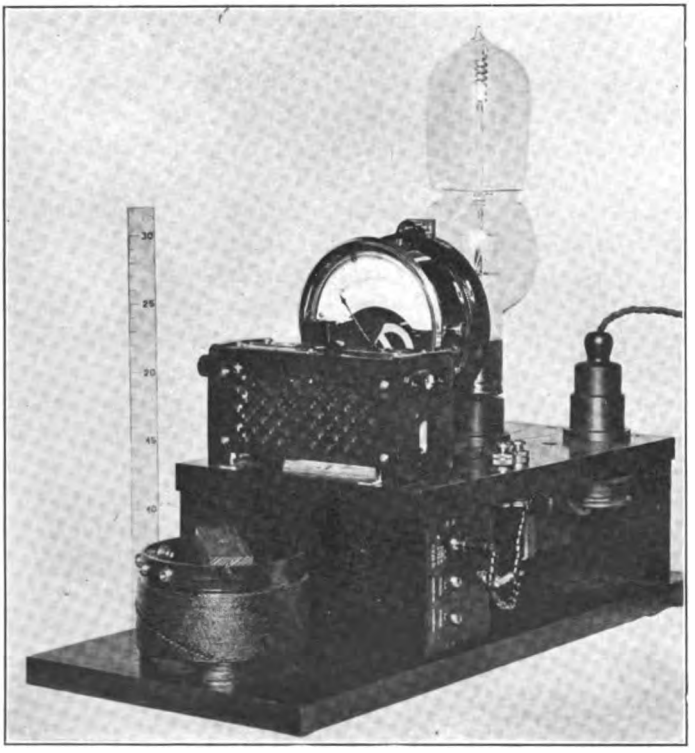

FIGURE 1

[2] German patent 290,256 of July 16, 1913, and English patent 13,636-13 of June 12, 1913.

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great interest in professional circles, and led to the result that the same vigorous investigation of this subject was carried out in America as in Germany and England.

It was attempted to increase the short operating life of the Lieben tubes by using self-renewing oxide-covered cathodes, various sorts of gas content for the tubes, and automatic valves for admitting air to the device. However, the limitations of output remained. Since the middle of 1913, the Telefunken Company has also investigated high vacuum tubes as well as gas-filled tubes, and, by the beginning of 1914, had completely gone over to the use of high vacuum tubes for reception. The establishment of its own vacuum pump installation and tube factory by the Telefunken Company, under the direction of Dr. Rukop, led to the work proceeding more rapidly, and since March, 1914, it was possible to carry on vigorously the production of high vacuum transmitting tubes as well. Figure 2 shows the first high vacuum tubes for transmission, dating from the beginning of 1915. They were built with open construction. The right-

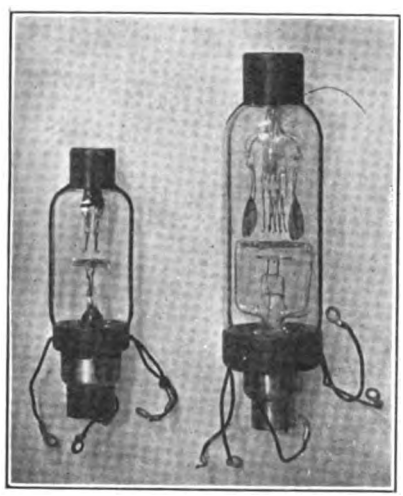

FIGURE 2

hand tube is seen to be provided with metal plates on each side of the filament in order to prevent electron streams which are produced by the magnetic field of the filament from reaching the glass walls. Figure 3 illustrates the first high vacuum tube transmitter (beginning of 1915).[3] This set was built for teleg-

[3] "London Electrician," 1914, page 702.

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raphy and telephony on a single wave, and receiver and transmitter were in the same case. The circuit is shown in Figure 4. The intermediate circuit is provided by the coils L_1 and L_2 and the variable capacity C. The grid is connected across a portion of the coil L_1. The plate voltage is obtained from the coil

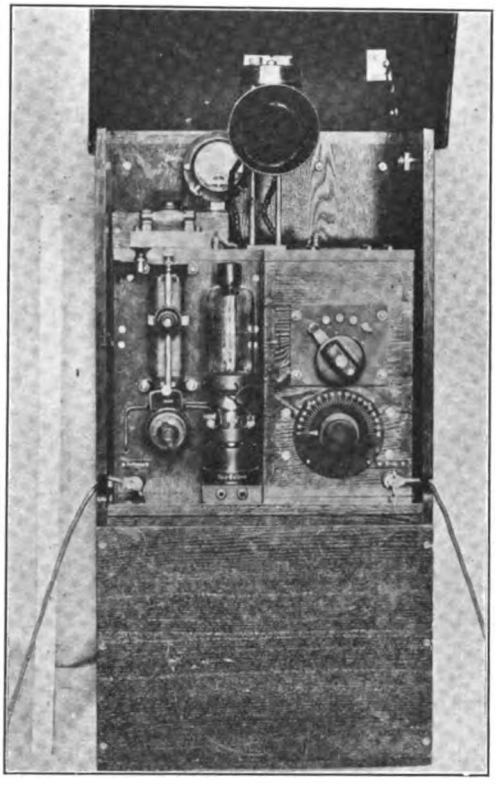

FIGURE 3

L_2. C_2 is a blocking condenser. The antenna is loosely coupled to the system thru a few turns of L_1. The plate voltage of 1,000 volts was provided by dry cells which were placed in the lower case of the transmitter. The filaments were lead by six-volt storage battery. The output of the transmitter was from 10 to 15 watts. Electrically considered, this is practically the same arrangement as the transmitter used experimentally by the Allies at the end of 1917 on the West Front.

In view of the great demands on the Telefunken Company's

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factories in connection with the production of receiving amplifiers, at that time, the further development of the tube transmitter was limited for a time. Because of this situation, it be-

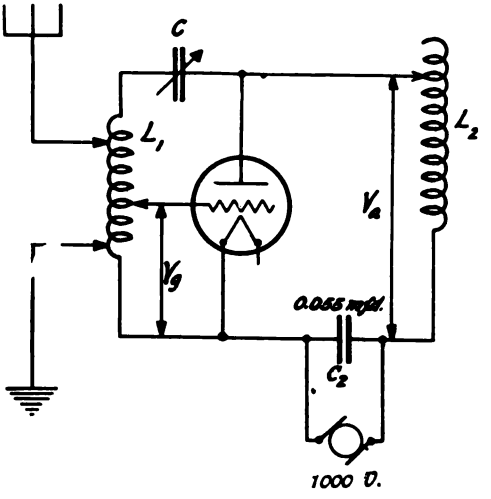

FIGURE 4

came necessary to develop high vacuum technique from the very beginning, and a whole series of physical and mechanical problems had to be solved. The work of Langmuir became known in Germany in 1915. A particular difficulty was experienced in the construction of the grid, and in securing it firmly in place. After attempts, lasting for months, to wind the grid on frames of hard glass, a satisfactory solution was found in the use of a construction due to the author wherein the grid was wound upon its own metal frames. This was so simple a matter that fine wire and narrow mesh grids, such as are necessary for tubes of high efficiency, were readily produced. Several forms of modern tube construction are shown in Figure 5. The plates are almost always made of tantalum sheet, the grids of tungsten. The usual sizes of tube deliver outputs in the antenna of 10, 75, 200, 500, 1,000, and 2,000 watts respectively. For higher powers, tubes are placed in parallel, as many as 20 being used in this fashion. Disturbing short waves, of approximately 100 meters wave length, appear quite regularly under such conditions, but are eliminated thru the use of small capacities, inductances, or resistances between the grid and filament or in the plate leads.

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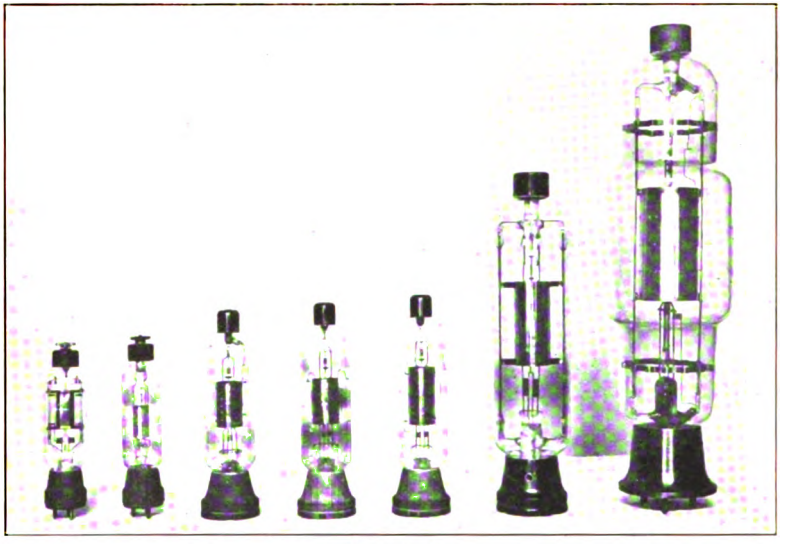

FIGURE 5

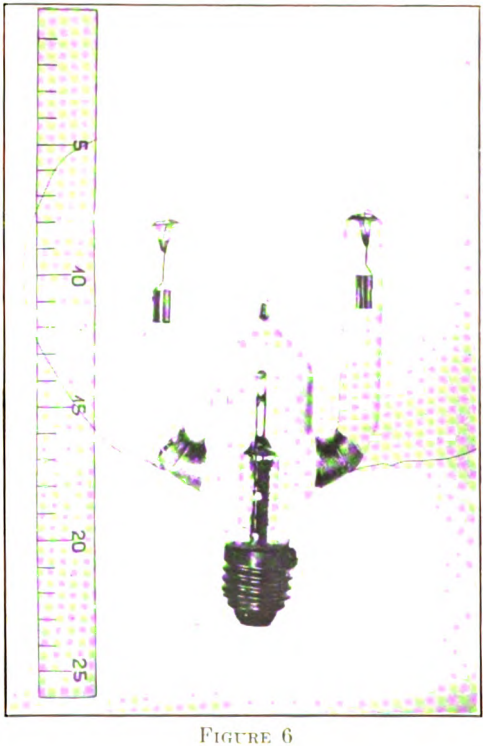

FIGURE 6

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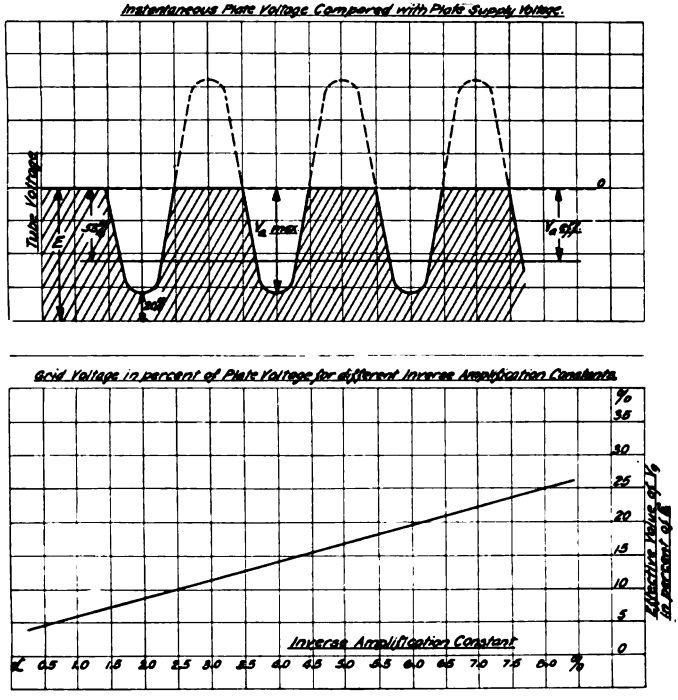
As sources of power for the plate circuit the following are available:

—for voltages up to 500, small direct current converters (dynamotors) with a single armature, operated from a 12-volt storage battery.
—from 1,000 to 2,000 volts, direct current generators.
—up to 3,000 volts, 50-cycle or 500-cycle alternating current, converted into direct current by an oxide cathode argon-filled rectifier produced by the Haagener Storage Battery Manufacturing Company.
—for voltages above 3,000, kenotrons or mercury arc rectifiers


Instantaneous Plate Voltage Compared with Plate Supply Voltage.
Tube Voltages
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Grid Voltage in percent of Plate Voltage for different Inverse Amplification Constants
Inverse Amplification Constant
Effective Value of Grid Voltage in Percent of Plate Voltage

FIGURE 7

The bases of the design of transmitters are always the simple relations which exist between the radio frequency voltages impressed on the plate and grid and the direct current supply voltage The effective alternating plate voltage is 45 to 60 percent of the direct current supply voltage (as shown in Figure 7, part 1), the

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grid voltage from 4 to 20 percent. Figure 7, part 2, shows the relation between the grid voltage and the inverse amplification constant.[4] If the output of any particular tube is known (for

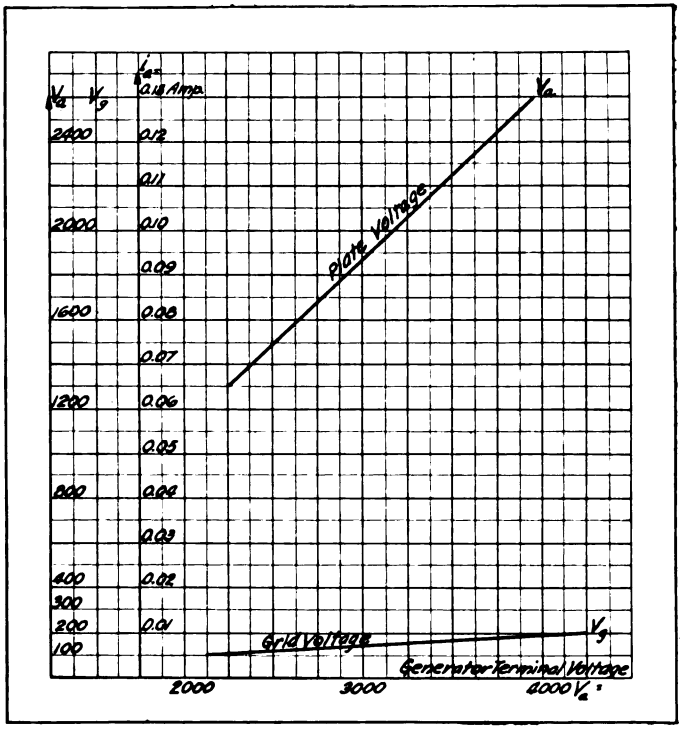

FIGURE 8

example, Figures 8 and 9 show the working curves of a 500-watt tube), and also the resistance of the oscillation circuit, then there can immediately be obtained for a transmitter with any chosen supply voltage and wave length, the values of the inductance or capacity which must be connected to the grid and plate. The condition which must be satisfied is that the above plate and grid voltages using inductive coupling must be equal to

$$2\pi n L I$$

or using capacitive coupling

$$\frac{1}{2\pi n C} I$$

[4] (The term "Durchgriff" has been translated as "inverse amplification constant" since it is the reciprocal of the amplification constant, as defined by van der Bijl (PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS, 1919, page 106) and Carson (PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS, 1919, page 188).—EDITOR.)

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regardless of whether the grid and plate have voltage applied to them directly or thru an oscillating circuit. If high efficiency is required, it is desirable to couple the plate circuit more closely to the oscillation circuit and the grid circuit more loosely. In

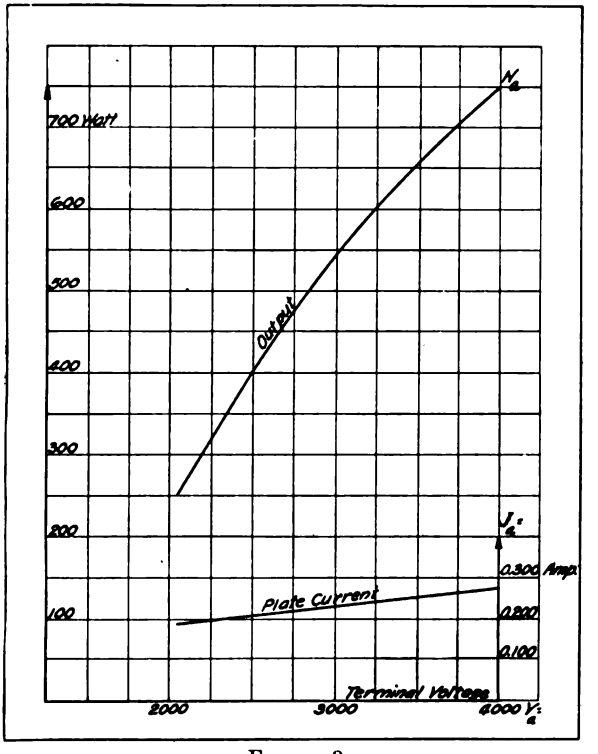

FIGURE 9

order to draw still greater output from the tube, there are produced in the plate circuits currents of special wave form (Rukop) or else an auxiliary voltage of triple frequency is impressed on the grid (Meissner). The losses are then greatly reduced, since during the operation of the tube the time during which the highest voltages are applied to the tube is reduced, and, furthermore, because at the time when the highest voltages are applied to the tube, the passage of current thru it is prevented. Under such conditions there will be produced powerful overtones or harmonic oscillations of higher frequency. When using transmitters directly coupled to the antenna circuit, such harmonic currents

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are avoided by the use of absorbing circuits or of an intermediate circuit, or by the control of a power tube amplifier by a small tube oscillator (German patent 298,484, Meissner).

Several forms of a modern transmitter will be described below. In the first transmitters, an inductance in the grid circuit was generally used either with or without grid circuit tuning, and more or less closely coupled to the plate circuit, either inductively or capacitively. In the latter transmitters, using more stable tubes, practically only direct coupling between the grid and plate circuits was employed. Figures 10 and 11 show a small type of transmitter, with an output of 20 watts, for use in the trenches. In order to meet the difficult military requirements for such a transmitter, it was designed for a continuous wave length range of from 300 meters up to almost 2,000 meters. The oscillating

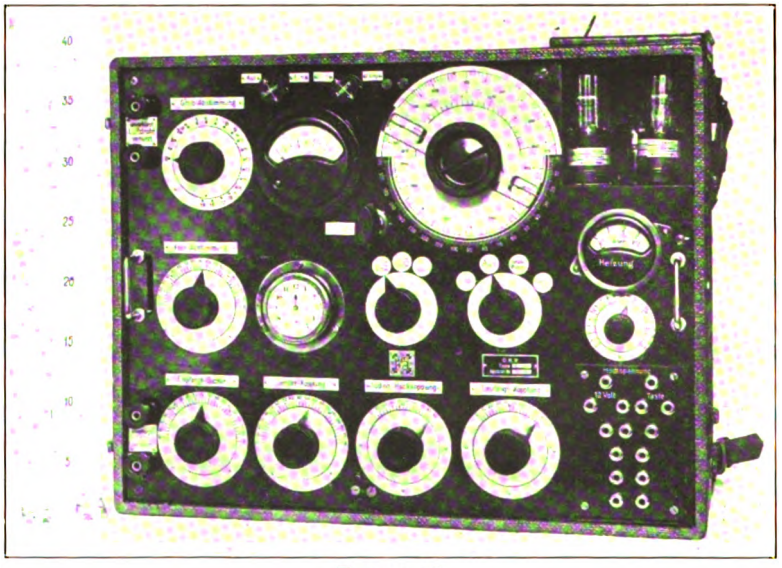

FIGURE 10

tube receiver is contained in the same case. The transmitter can be used with any desired antenna. These requirements could be met only thru providing the transmitter with an intermediate circuit.

An aircraft transmitter and receiver are illustrated in Figure 12 and shown with the cover removed in Figure 13. In this case as well, a long range of wave lengths from 300 to 750 meters is

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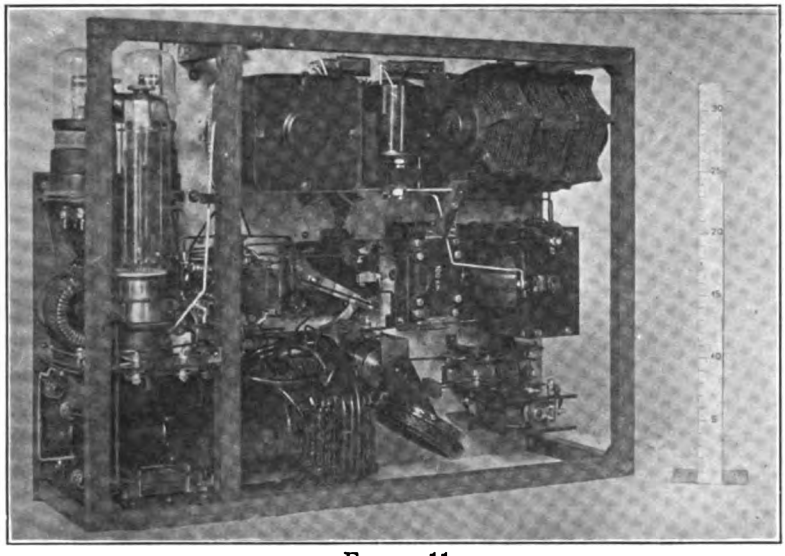

FIGURE 11

provided. The transmitter is set to a definite wave length while on the ground, and the antenna is tuned in flight. The operator then has no further opportunity to alter the circuits. For radio telephony, the microphone transmitter is generally inserted into the antenna.

A very simple 20-watt transmitter for use on two wave lengths is shown in Figure 14. It is arranged for two-way opera-

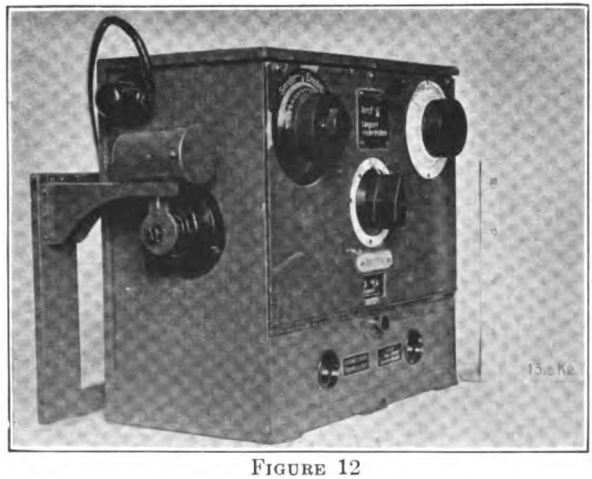

FIGURE 12

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tion. The right hand case contains the tuning circuits necessary for this purpose, together with the tube detector and three-step amplifier. This set is intended for radio telephony between fishing boats. The speech voltages in this set are introduced into the grid circuit in series with the radio frequency voltages.

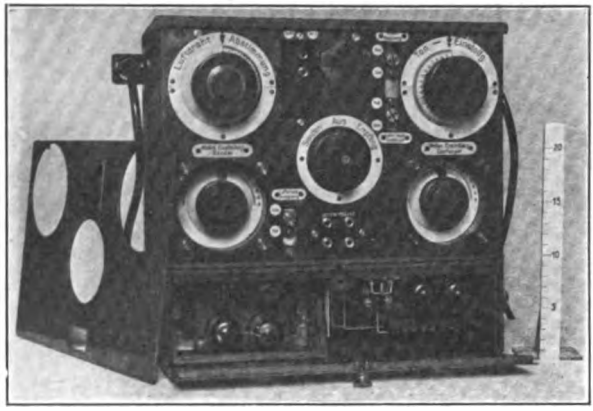

FIGURE 13

Figure 15 shows the schematic circuit of a one-kilowatt tube transmitter. Both filament and plate voltages are obtained from the same 500-cycle alternator of 1.5 kw. output. The transmitter is provided with two 500-watt tubes, requiring four amperes and six volts for the filaments; while the alternating current is rectified by an oxide cathode rectifier using five amperes and two volts. T_1, T_2, and T_3 are the three filament cur-

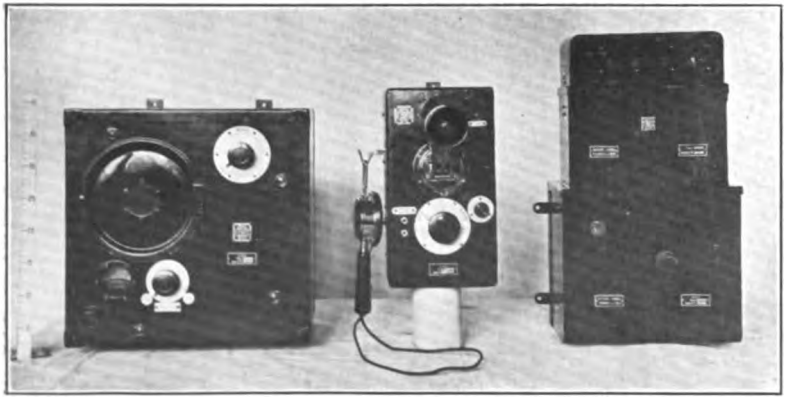

FIGURE 14

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rent transformers. To avoid changes in filament current while operating, due either to variations in the speed of rotation of the alternator, or due to fluctuations of the load in the plate circuit when transmitting, a compensation transformer, T_v, is provided.

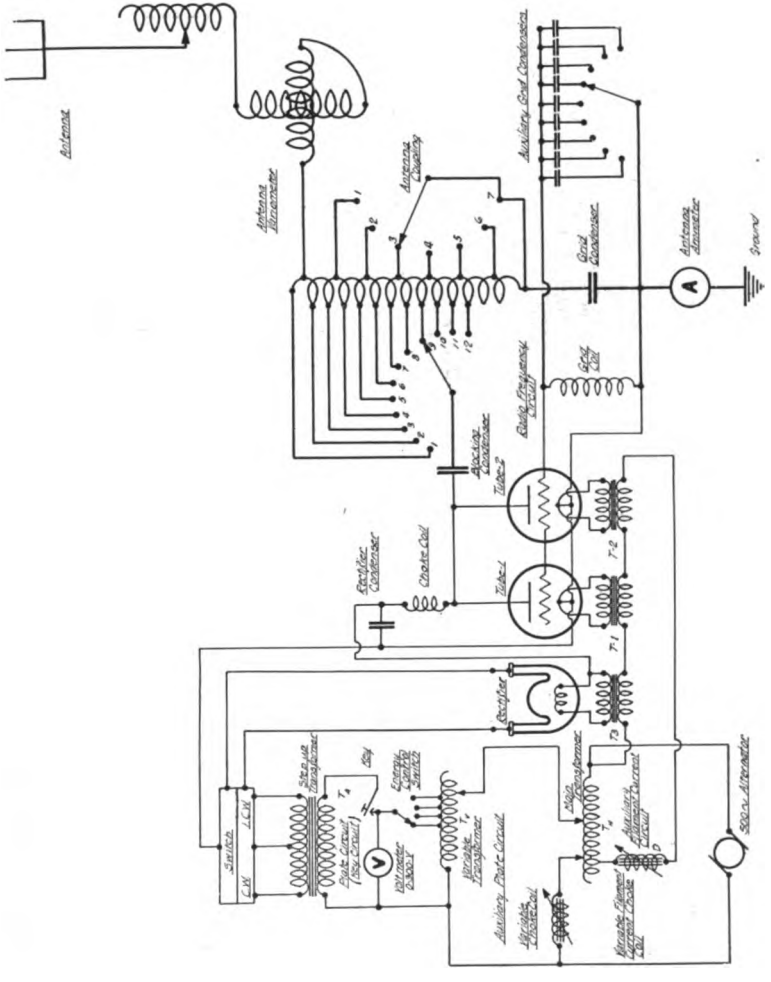

FIGURE 15

This is an open core auto-transformer, with several taps for different outputs, which is connected to the high-voltage plate current transformer T_a. The compensation for load is accomplished by T_h. When the key is depressed, the main current induces an extra voltage in T_h which, with correct adjustment of the choke

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coil D, compensates for the effect of the drop in voltage of the machine, resulting from the increase in load when the key circuit is closed. Thus the filament current remains unchanged. Energy passes from the high-voltage side of the transformer T_a to the rectifier and the tubes thru a switch arranged for transmission either with or without a musical tone. For transmission without tone, for the sake of simplicity the rectifier condenser is disconnected from the circuit. This transmitter was much used on the submarines. Figure 16 shows its appearance when provided to cover a continuous range of wave lengths. To the left

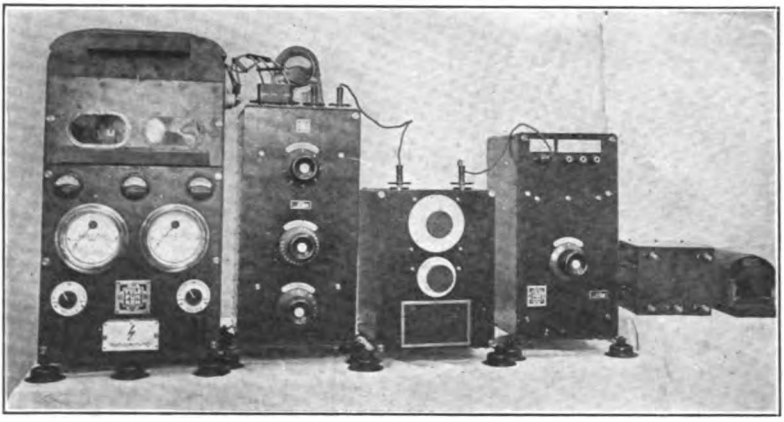

FIGURE 16

is a container holding the bulbs, rectifier, and transformers, and next to this a case containing the plate and grid couplings. The third case contains a variometer and the fourth the antenna loading coils for use on exceptionally long waves. Figure 17 shows a recent form of this transmitter for several fixed waves. In these sets, a new type of antenna loading inductance is used, which is shown in Figure 18. These are constructed according to a method given by the author (German patent 309,203), involving the use of multi-layer coils so arranged that between all cross sections there is the same separation of several millimeters. This design leads to the smallest possible damping where large inductances are required of fairly small volume. One-kilowatt transmitters are now used in several of the larger German cities in connection with the postal service network and especially for press service. When these transmitters are used for radio telephony, a tube is inserted

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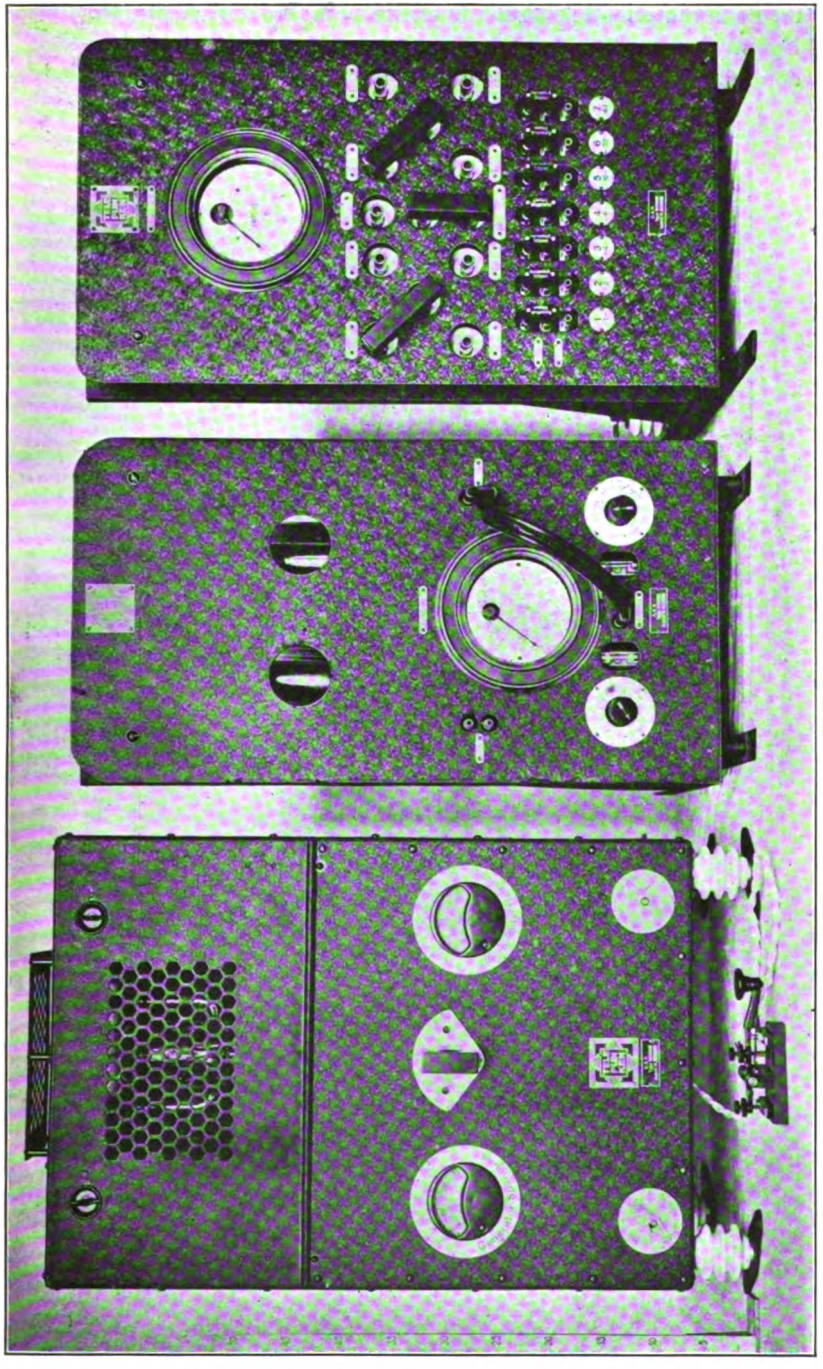

FIGURE 17

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into the plate lead so that the entire plate current passes thru it. By impressing the amplified speech voltages on the grid of this control tube, the plate current of the main tube is suitably varied.

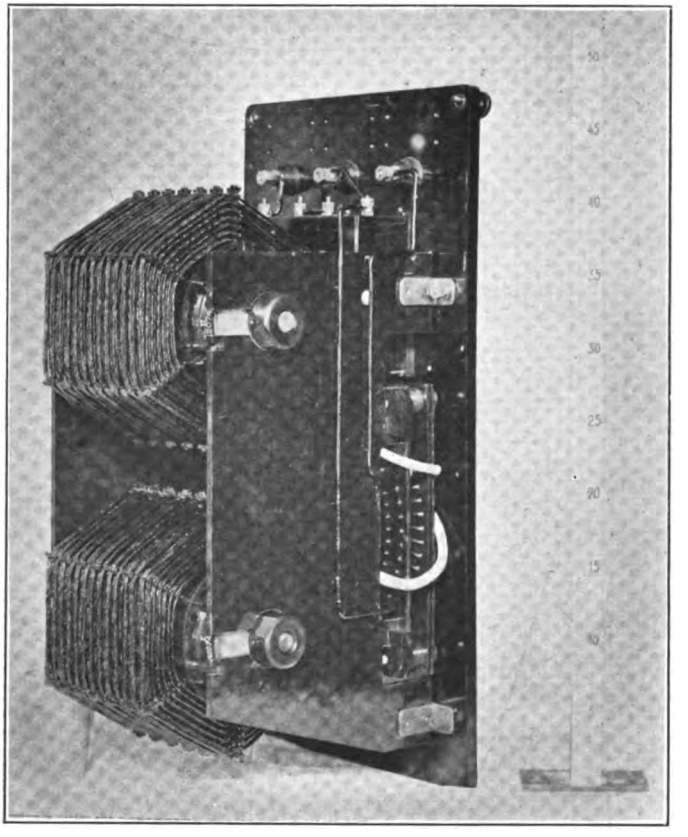

FIGURE 18

A tube transmitter using 20 bulbs in parallel is shown in Figure 19; and another transmitter with 8 tubes, each delivering 1.5 kw. and placed in parallel, is illustrated in Figure 20. In these larger tube transmitters, both telegraphy and telephony are carried out by the master control system; that is, a small tube transmitter of approximately 1 kw. output is used to impress the necessary voltages on the grids of the larger tubes. Such transmitters have been used for some time in Königswusterhausen and Prague with entire satisfaction, and it is

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expected shortly to carry on the transmission of press material for all of Germany by means of such a set.

The apparatus developed for radio telephony has found a large field of usefulness for multiplex telephony along conductors ("guided radio"). Even during the war experiments were carried

FIGURE 19

out by the Telefunken Company in telephony along wires by using radio frequency currents, and also, in cases of need, for telephoning over broken conductors. While the researches carried on at that time did not lead to finished apparatus, they furnished the basis for the later development of this process and for its use on a larger scale immediately after the end of the war for the improvement of the German Post Office telephone network. At the present time, a considerable number of channels of communication using radio frequency multiplex telegraphy are in existence in Germany for distances up to more than 600 km. (375 miles). Some of these have been in use with excellent results for over a year. In general, two radio frequency communications are carried on over each wire. The wave length range employed is between 5,000 and 20,000 meters. Speech modulation is obtained thru direct control of the plate voltage or thru

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separately excited generator tubes. In order to operate with the least possible intermediate amplification and the simplest circuits, fairly considerable power is employed (from four to eight watts), resulting in currents in the conductor of 0.1 ampere. The protection of the receiver from the transmitter is accomplished thru a suitable choice of the radio frequency resistance of the circuits or thru Wheatstone bridge circuits. Figure 21 gives a view of the radio frequency room of the Berlin central or ex-

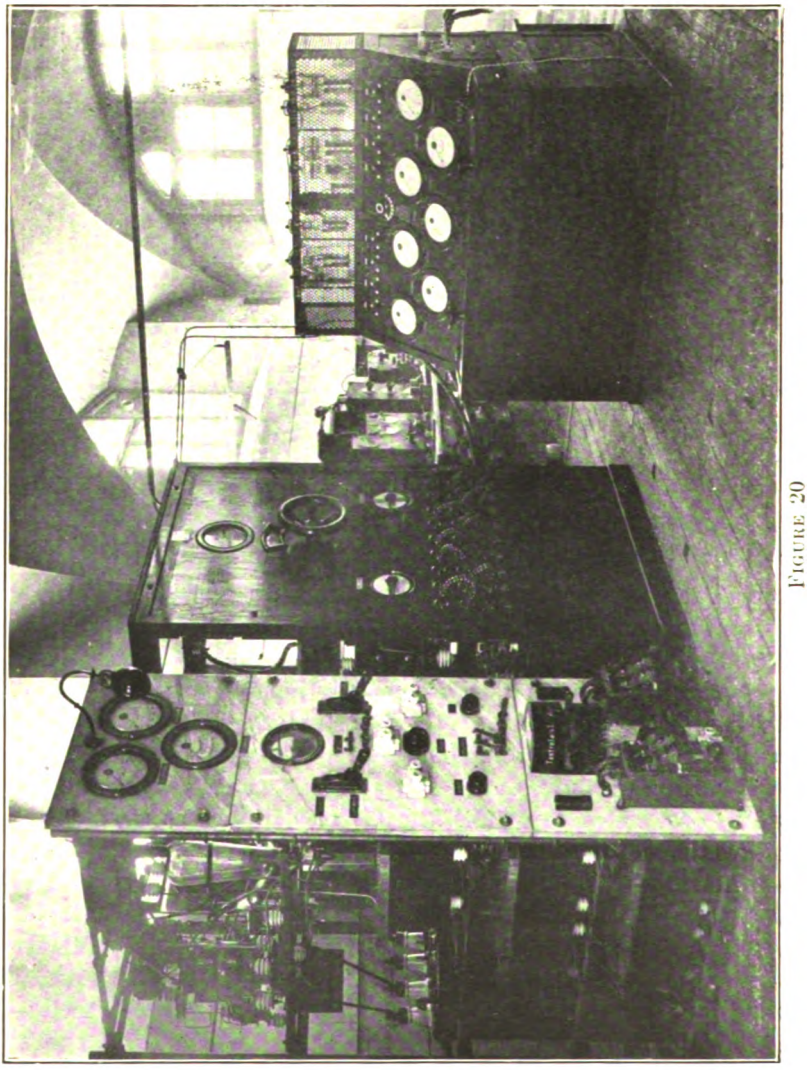

FIGURE 20

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change. To the right can be seen the transmitters, and to the left the receivers, while in the middle are shown the circuits necessary for connecting the receivers and transmitters properly to the nearby central equipment. Figure 22 shows a small set for multiplex telephony. Multiplex high speed telegraphy

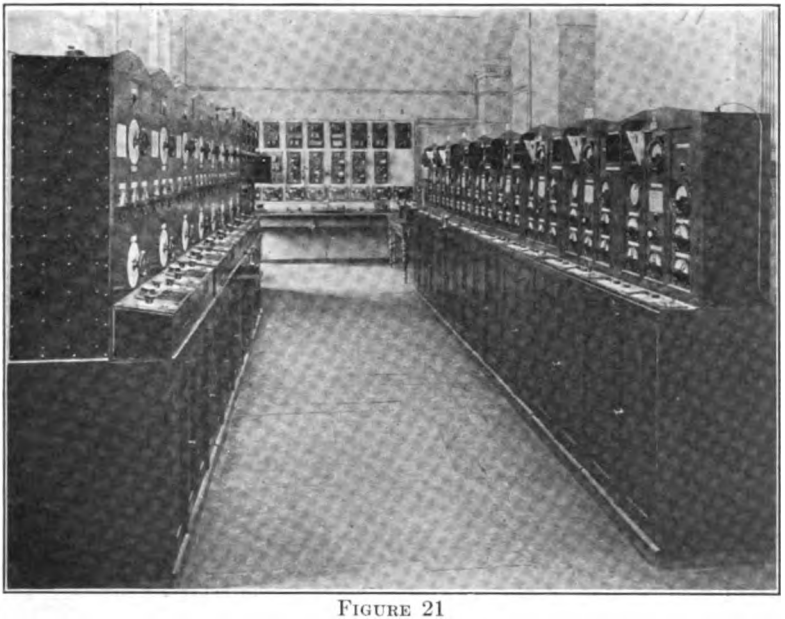

FIGURE 21

on a single wire (quadruplex-duplex) has been established between Frankfort and Berlin, permitting perfect transmission of 4,000 words per minute. For this purpose there are generally used shorter waves than for telephony (below 8,000 meters). The Siemens high speed telegraph equipment (printing telegraph) working at 600 to 1,000 letters per minute, which is here used, is an ideal solution, and is also equally applicable to high speed radio service.

Figure 23 shows a transmitter for telephoning along high voltage lines, such as is now frequently used to connect the large power plants with their sub-stations. Such transmitters are provided with a simple modulation system with direct application of the speech voltages to the grid. In view of the low damping of high voltage lines and the short distances generally covered by such sets (usually less than 200 km. or 125 miles), these transmitters work at wave lengths below 2,000

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FIGURE 22

meters. The apparatus is built in very rugged form, is provided with two 10-watt tubes, and is arranged to work thru the line even if the line switches are open. A call signal device is provided with this set. Transfer of the radio frequency energy to the line is thru either one or two wires stretched parallel to the high voltage line for a distance of about 100 meters (300 feet). Recently these sets have generally been connected to the line directly thru small capacities or else the leading-in insulators are arranged to serve as such transfer capacities.

SUMMARY: The development of gas-containing and high vacuum transmitting tubes in Germany is described. The main forms of tube transmitters are illustrated and their circuits given. The application of such transmitters to multiplex telephony or telegraphy along high voltage lines is described.

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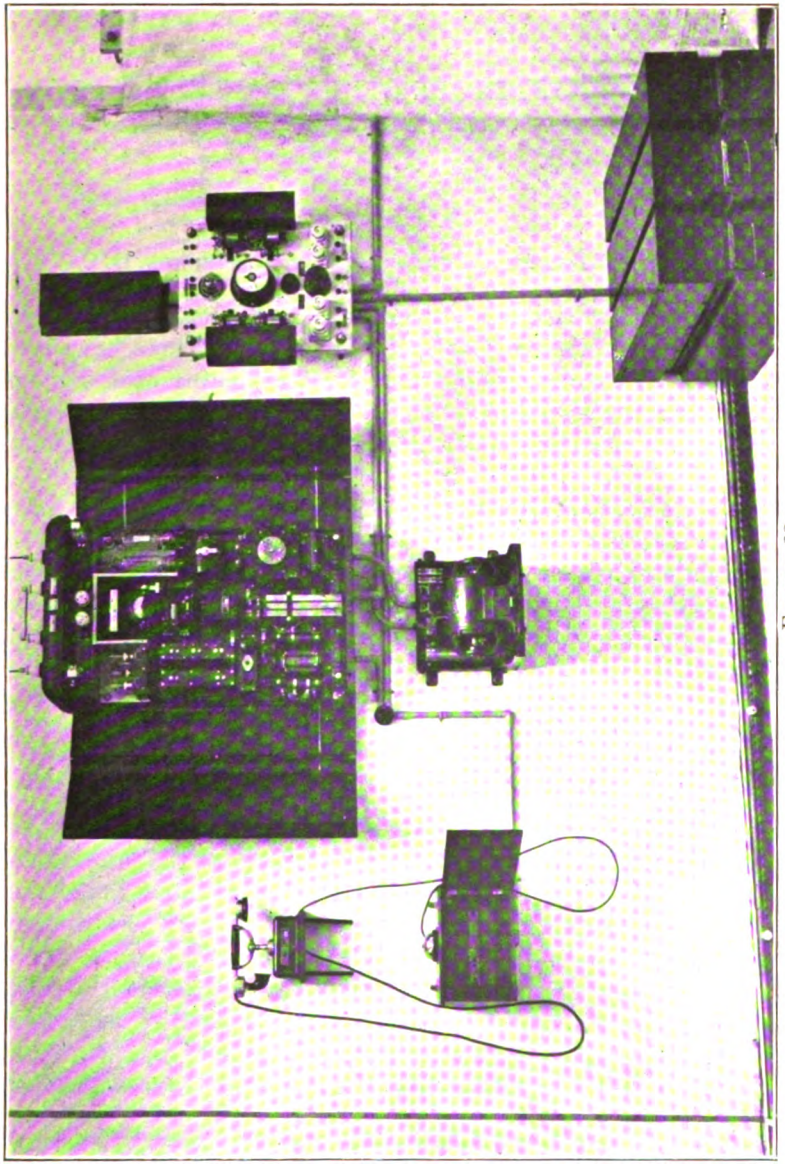

FIGURE 23

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IMPROVEMENTS IN PILOTING CABLE RECEIVING APPARATUS*

By

A. Crossley .

(Expert Radio Aid, Navy Department, Washington, D. C.)

Since the writing of a previous article on "Piloting Vessels by Electrically Energized Cables"[1] many improvements have been made in the receiving apparatus for the piloting cable system. These improvements have greatly increased the effective range of the receiving apparatus which in turn reduced the power input into the cable.

The object of this paper is to describe the improvements made in the receiving apparatus and thereby add to the meager information now available on the subject of piloting vessels by means of electrically energized cables. The following paragraphs describe the different stages of development of the apparatus and the general characteristics of the final model of piloting cable-receiving equipment, which is now being given service tests in the New York Harbor.

New London Experiments

During experiments conducted at the Submarine Base, New London, Connecticut, an attempt was made to tune the receiving apparatus to resonance by means of a 0.0025 microfarad variable condenser (air dielectric) inserted in series with the 240-turn four foot (1.3 m.) square collector coil and the primary of the first audio frequency transformer of the SE-1600 two-stage audio frequency amplifier. A schematic diagram of this circuit is shown in Figure 1. Due to the small value of capacity of the condenser only a slight increase was noted in the strength of the received signal from cable.

Efforts were made to obtain condensers of larger capacity at the Submarine Base, but no condensers were obtainable that were of a capacity less than 1 microfarad. Further experiments

*Received by the Editor, June 30, 1921.

[1]See Proceedings of The Institute of Radio Engineers, volume 9 number 4, August, 1921, page 273.

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to improve the apparatus were not attempted at New London, in view of the lack of proper condensers and other laboratory equipment.

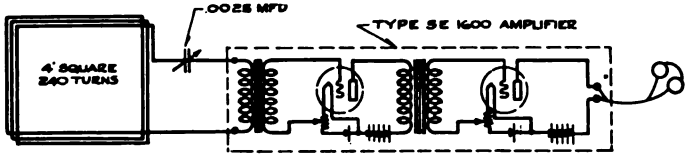

FIGURE 1

NEW YORK EXPERIMENTS

The experimental work was continued at New York in November, 1919, but because of defective cable installation and the delay incurred in obtaining new cable and installing it in the New York Harbor, the major part of the experimental work was not undertaken until August, 1920.

During the interim between October, 1919, and August, 1920, various types of receiving circuits were evolved by the writer for test by the New York Navy Yard, and arrangements were made to test these circuits immediately when the cable was available to determine the relative merits of each circuit. In order to expedite the experimental work, the New York Yard was requested to construct and test three types of coils having 400, 600, and 800 turns of number 20 double cotton covered wire[2] wound on a wooden frame four feet (1.3 m.) square, to determine which coil received the greatest power from the cable. When tested the 800-turn coil gave twice the signal strength of the 400-turn coil and one-third greater strength than the 600-turn coil. The results were in accordance with theoretical conclusions, and showed that the problem was the same as any straight electrical engineering problem and could be handled in the same manner. Upon reviewing the results of these tests and after noting the weight of the respective coils it was decided that the 400-turn coil would be best suited for the receiving system. This decision was based on the fact that the 800-turn coil was too heavy to be classed as portable and the loss of signal strength when using the 400-turn coil could be easily made up by a slight increase in power input in the amplifier. Having decided upon the 400-turn coil, in view of its portability, measurements were

[2]Diameter of number 22 wire = 0.032 inch = 0.082 cm.

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made to determine the impedance at 500 cycles of this coil. The result of these measurements showed that the average impedance of a number of 400-turn coils was 2,000 ohms.

Working on the principle of maximum power transfer from one circuit to another, the Washington Navy Yard was requested to manufacture an audio frequency amplifier, the primary of the first audio frequency transformer of which was to have an impedance of 2,000 ohms at 500 cycles. This primary was to be connected direct to the collector coil and thereby produce an ideal condition for the maximum power transfer inasmuch as the collecting and input circuits were of equal impedance.

To check the theoretical conclusions of the efficiency of the new circuit, experiments were conducted on board the United States steamship *Algorma*, with the new type amplifier and the regular SE-1600 two-stage amplifier in conjunction with the 400-turn coil. The primary of the first audio frequency transformer of the SE-1600 amplifier when measured was found to have an impedance of 30,000 ohms at 500 cycles. The outcome of the tests on the *Algorma* showed that when directly over the piloting cable, the audibility of the received signal when using the SE-1600 amplifier was 500, while when using the new type amplifier the audibility recorded was 10,000 or an increase of 1,900 percent.

The excellent results obtained with the new circuit caused the writer to investigate the cause of the efficiency of the circuit, and especially to consider the idea that the great increase was due to the use of equal impedance in the collecting and input circuits. Upon closer study of the circuits it was noted that one other factor had to be considered, namely, the step-up ratio of the transformer. The step-up ratio of the new transformer was found to be one to ten while the original transformer had a ratio of one to three. Considering the increased step-up ratio of the new transformer as producing approximately three times the original voltage on the grid of the first vacuum tube, it may be granted that the use of equal impedance was responsible for the greater part of the increased signal strength and therefore is of importance in the design of piloting cable receiving equipment.

The encouraging results obtained with the new circuit led the writer to suggest a further improvement in the equipment wherein another attempt should be made to tune the circuit to resonance by means of a suitable condenser placed in series with the primary of the transformer and the collector coil as shown in Figure 2. The total inductance of the collector coil and the

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primary of the transformer was measured and the value substituted in the formula, $F = \frac{159.2}{\sqrt{LC}}$, where F is the frequency of the received signal, L the total inductance in henrys, and C the capacity in microfarads, in order to obtain the value of capacity needed for tuning the circuit to resonance at 500 cycles. The result of substituting the value of the total inductance in the formula showed that a 0.05 microfarad condenser would be required to tune the circuit to resonance.

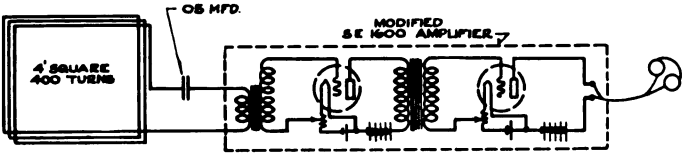

FIGURE 2

Experiments were again conducted on board the *Algorma* to determine the value of tuned circuits. In order to obtain low audibilities of received signals from the cable for comparison purposes, it was necessary for the *Algorma* to operate close to the channel buoys, which position was approximately 1,100 feet (360 m.) from the piloting cable. In this position with the equal impedance circuit the audibility of the received signal was ten, when while using the tuning condenser the audibility was increased to 100 or an increase of 900 percent. During these experiments it was noted that there was an optimum position for the coils with respect to the side of the vessel and this position is shown in Figure 3, at an angle of fifteen degrees to the side of the vessel. In this position the beneficial shielding effect of the hull of the vessel assists to a great extent in sharpening the differences in strength of received signals from the respective collector coils and thereby telling the operator which coil is nearer to the cable. The close proximity of the coil to the steel hull of the vessel was thought to have an effect on the proper tuning of the circuit by increasing the inductance of the coil, but because of the lack of time this subject was not investigated, especially since the signal received with the new equipment was sufficient for all practical needs.

During the experimental work with the tuned circuit, signals were heard at a distance of 1,000 yards (980 m.) from the cable, which was supplied with the usual current flow of three amperes.

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This distance is a very important factor from a navigational standpoint, for with a given radius of 1,000 yards from the cable it will be comparatively easy for the pilot or person conning the vessel to pick up the cable, which previously was not possible with the old equipment, due to the limited range of the receiving equipment.

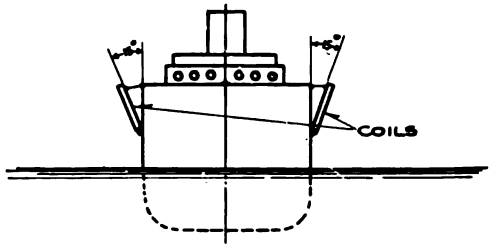

FIGURE 3

DESCRIPTION OF APPARATUS

Having satisfactorily developed the receiving apparatus to meet service requirements, the New York Yard was instructed to proceed with the design of the equipment, which would incorporate a two-stage audio frequency amplifier and a special switching device, which device would allow the use of one or two stages of amplification and the tuning condenser.

A front view of piloting cable receiver is shown in Figure 4. As shown, the receiver is placed in a watertight container and has only two switches (2) and (3); switch (2) connects either the port or starboard coil to the receiver while switch (3) connects the coil to the telephones in the "Off" position, one stage of amplification in position (1), two stages of amplification in position (2) and two stages of amplification with tuning condenser in position (3). Vacuum tube plate batteries, one spare vacuum tube, and a spare ballast lamp for the filament circuit are included in the container, the only external accessory being the 6-volt storage battery for supplying current to the filaments of the vacuum tubes. This battery can be placed in the chart house and connected to the receiver by armoured cable thru the middle stuffing tube shown in the lower part of the receiver.

The collector coils are suspended over the opposite sides of the vessel by the means of a special fitting which is shown in Figures 5 and 6. This fitting renders the coils portable and easy to handle when entering and leaving port. Armoured cable

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connects the coils with the two other stuffing tubes in the base of the receiver, and from there to the respective binding posts on the panel. The cable connection to the coil is made with a special watertight box which is situated on the upper part of the coil. The two binding posts at the bottom of the receiver marked "Telephone" connect to the telephone receivers, which can be stowed in the compartment under the panel. The

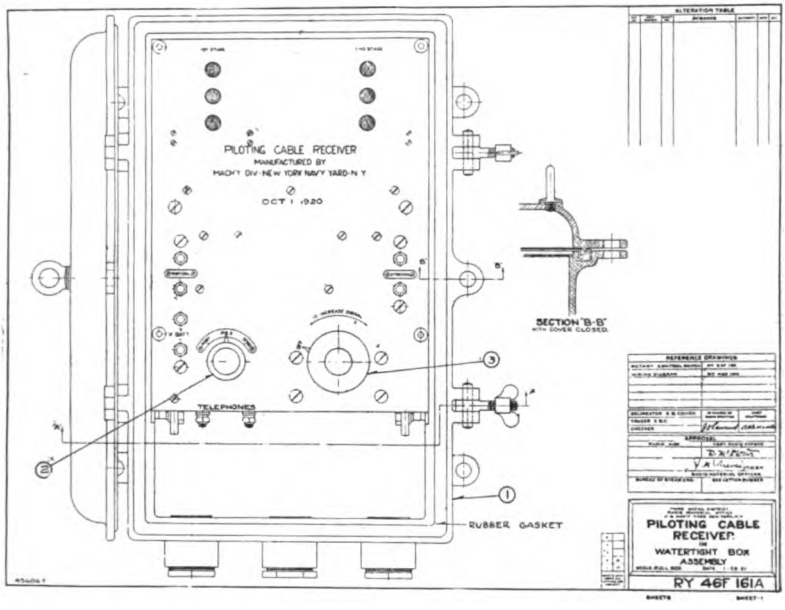

FIGURE 4

interior of the receiver is accessible for renewal of batteries, and so on, by removing knurled nuts on the front of the panel and pulling the panel forward until it stops.

Ballast lamps are used in the vacuum tube filament circuit and automatically regulate the current flow over a voltage range from 4.5 to 6.5 volts, so that the current is maintained at 0.65 ampere for each tube. These lamps eliminate the usual rheostat and trouble experienced due to the tendency of operators to burn the filaments at a greater brilliancy than is necessary for reliable operation, thus shortening the life of the tubes.

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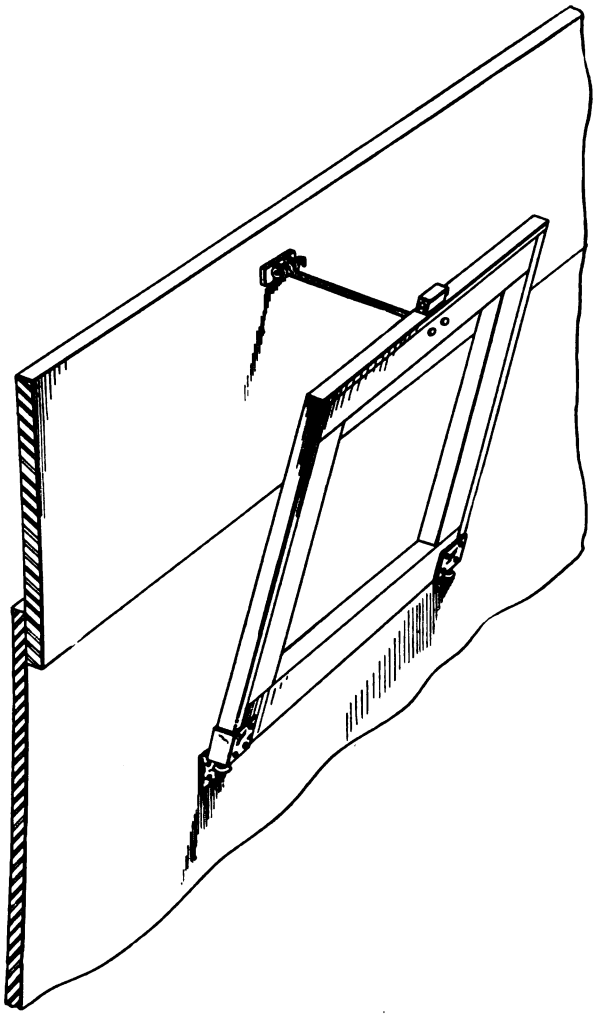

FIGURE 5

CONCLUSIONS

The piloting cable receiving equipment in its present form fulfils all the requirements for the aural method of reception. The use of two stages of amplification with the tuning and equal impedance features covers reception of signals when first picking up cable at entrance to harbor, while the application of one or two stages of amplification is sufficient for following the cable into the harbor either by steering directly over the cable or to the starboard side of cable at any desired distance.

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The switching devices on the receiver are simple in operation and easily mastered by the average person, while the ballast lamps render the apparatus foolproof. The watertight container permits the installation of the receiver at any part of the bridge where easy access is had to the equipment when needed.

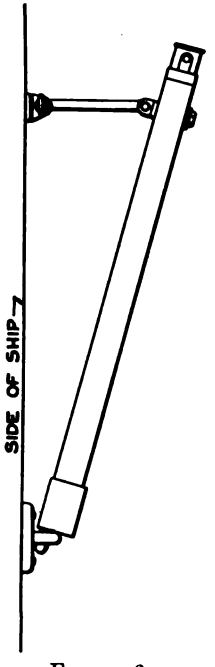

FIGURE 6

Using the four-foot (1.3 m.) 400-turn coils with receiver, no additional apparatus is necessary for entering any harbor the channel of which is not deeper than 200 feet (60 m.). The equipment is easy to install and of such size as not to interfere with other structures on board ship, while the coils can be rigged over the side when in use and stowed away when alongside dock or at sea.

Altho the equipment described is satisfactory for immediate application as an aid to navigation it may be stated that many improvements will be made on this equipment in the near future, but such improvements will generally consist of refinements of the basic equipment described in this paper.

The extreme simplicity of the apparatus and the ease by

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which it is applied to navigation are factors which favor the early adaption of the system and the only factor which will retard its early adaption is the present absence of cable installations in the different harbors other than New York Harbor. The future installation of cables in the important harbors will most likely be undertaken in the near future, when further information is obtained on the operation of the new cable which is to be installed in the New York Harbor during the month of August, 1921.

Word has been received from England and France telling of the advance made with the piloting cable system and of the installation of permanent cable systems in certain harbors of these countries. This news is gratifying inasmuch as it shows the importance of the application of the system and promises a great future for this new aid to navigation It is the opinion of the writer that the piloting cable system will soon take its place with radio telegraphy and the radio compass as one of the chief aids to nagivation.

In concluding the writer desires to state that this work was conducted under the supervision of Commander S. C. Hooper, U. S. N., of the Radio Division, Bureau of Engineering, Navy Department, and that the writer and Expert Radio Aid, H. J. Lang, of the New York Yard, were instrumental in developing the apparatus to its present state.

SUMMARY: The further development of an aural receiver for the piloting cable system of guiding ships into harbors is described. In particular, the choice of a detecting coil of the most desirable number of turns, the proper choice of transformer input impedance and step-up ratio, and the use of audio frequency tuning of the coil circuit are discussed. The design of the latest coil, receiver, and amplifier is given.

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FURTHER DISCUSSION ON "PILOTING VESSELS BY ELECTRICALLY ENERGIZED CABLES"*

BY A. CROSSLEY

H. P. Rivers-Moore (by letter):† Mr. Crossley's paper on the "Audio Frequency Piloting System"— known in this country as "Leader Gear"—as published in the PROCEEDINGS for August, 1921, makes no allusion to the distortion of the lines of magnetic force resulting from the conductivity of sea water, and the diagrams given completely ignore this phenomenon and treat the lines as circles about the submerged cable as centre.

In May or June of 1918 I was asked to begin a research on the possibility of using a submerged cable carrying current as a means of navigation, on behalf of a Department of the British Admiralty engaged in experimental work connected chiefly with anti-submarine work. My first experiment was to take a coil about three feet (1 meter) square in a small motor boat and investigate over an existing loop of cable laid at the mouth of a harbor in about four fathoms (7.8 m.) of water and supplied with interrupted direct current of 1.5 amperes at 500 interruptions per second. It was expected that in a wooden boat at least, the maximum strength of signals would always be obtained when the coil was in a plane directed towards the cable. At the first trial I reported that at a distance of upwards of 50 yards from the cable the flux appeared to be perfectly horizontal. I wrote "under the conditions of test in a rocking boat the exact angle for maximum or minimum could not be determined, but within the limits of accuracy obtainable the positions appeared truly vertical and horizontal."

It seemed evident that this result was due to distortion owing to the fact that the magnetic flux was partly in a partial conductor and partly in air and, as a method of approaching the problem theoretically I considered what must happen as the flux was built up round the cable by the increasing current in it. The effect of the conducting medium would be to diminish the rate at which the lines of force would be propagated, but as long as the lines were totally within the medium they would remain as circles. (See Figure 1.) As soon, however, as a line broke surface it would be propagated at normal speed thru the

*PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS, August, 1921, page 273.

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air. The resulting distortion is indicated in Figure 1 and shows the sort of angles of the lines of force to be expected near the surface of the water.

FIGURE 1—Suggested Distribution of Magnetic Field About a Submerged Cable Carrying Alternating Current

To test this theory, I then made a number of experiments in calm weather with wooden boats, using a coil pivoted about a horizontal axis and also capable of rotation about a vertical axis so that the horizontal axis could always be maintained parallel to the cable. A pointer and scale enabled angles to be read with considerable accuracy.

An example of the results obtained is given in Figure 2 which completely bears out the predicted distribution of field. It also indicates the remarkable fact that the original idea that the coil would always give maximum signals when pointing towards the cable is not merely inaccurate but, at quite a short distance from the cable, directly erroneous. The diagram is drawn to scale and the depth is nearly ten yards (9.8 m.). It will be seen that at a distance of only fifteen yards (14.8 m.) on either side of the cable the coil would be horizontal for maximum strength of signals and beyond this would actually point more and more steeply *away from* the cable.

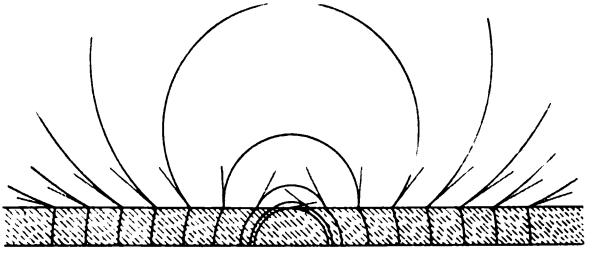

FIGURE 2—Supposed Distribution of Magnetic Field About a Submerged Cable Carrying 3 Amperes at 500 Cyles Per Second, Derived from Determination of the Direction of Field at the Surface Over a Long Cable

Considering now the case of two coils hung vertically on either side of a vessel and neglecting for the moment any screening or distortion due to the ship. The use of this method depends on

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the assumption that the coil farthest from the cable will give the weakest signals. Early in the course of the experiments and before I had fully recognized the extent of the distortion and its practical effect, I was directing the ship which had laid a special "leader" cable on its return voyage. I had not kept continuous watch but when still out of sight of land and approaching sand banks, I was asked to say which side the cable lay. I compared the signals from two vertical coils rigged port and starboard and said the cable was on the landward side. We made in that direction but signals were shortly lost. I was so sure of my result that I assumed the current had failed and we kept on the same tack hoping to pick up signals later. It was not until we sighted a wreck, piled up on the sands, that we realized we were well out of our proper course and in some danger of running aground. Needless to say the navigating officers had no more use for the cable and I returned nonplussed and discomfited. Later when the results given in the above diagrams had been secured and investigated I saw that if screening did not intervene it was quite possible that in any position beyond the region of vertical field the coil furthest from the cable would actually embrace a greater flux than that nearer to it owing to the fact that the field further out was more horizontal and therefore more favorable to a vertically suspended coil. The further coil would thus give the louder signals.

It appeared, and still appears, to me, that this accident was one which shows the method of two vertical coils to be a somewhat hazardous one. The vessel in question was of steel but the coils were placed above the decks and were evidently not efficiently screened. It is therefore most important that any vessel fitted in this way should be thoroly tested for screening effect and the coils carefully placed, since, apart from screening, the field due to the cable will actually give directly opposite readings to those expected and necessary for correct navigation, except over a narrow area quite close to the cable.

I put forward proposals for avoiding this difficulty. One was to use two triangular coils of few turns and large area rigged somewhat after the manner of a pair of directional radio aerials. These coils should preferably be set at an angle of 45 degrees to the keel line of the ship. Switching from one coil to the other is now equivalent to rotating a coil about a *vertical* axis and the distortion of the field due to the sea water has no effect on the directional results obtained. The coil which is most nearly parallel to the cable is the one which gives loudest signals. If

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the signals are growing stronger the ship is approaching the cable; if weakening, she is leaving it. When running parallel to the cable, signals are of equal strength in both coils.

Mr. R. H. Marriott, with his demand for simplicity in the receiving apparatus, will probably agree with me in preferring the alternative device which I recommended, namely to use a single horizontal coil, with or without amplifiers. Figure 3 gives general indication of the strength of signals obtained when passing across a leader cable and listening with a horizontal coil. When close over the cable there occurs a maximum, zero, and another maximum in rapid succession. This is an indication very

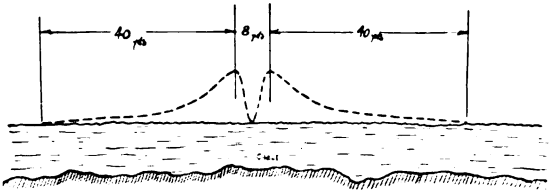

FIGURE 3

easy to observe. My method, therefore, used to be to direct the helmsman to steer in the general direction of the cable. I should then know at once when it was crossed. Knowing also the general lie of the cable and our course by the compass, I should know whether it then lay to port or starboard. I would turn the ship pretty sharply back towards the cable and note when it was crossed again, observing by the length of time that elapsed whether we were still approaching it steeply or gradually. After a few changes of course in lessening degree we should soon be running fairly parallel to the cable. In open water it was not necessary to keep always within touch of it as long as we knew which side it lay. Owing to the horizontal disposition of the field at a distance from the cable it is useful to swing the coil into a vertical position when first searching for the cables in this position the range of detection is much greater.

It is interesting to observe that the distortion at the surface is obtained with a cable laid on the ground. The lower half of the field is retarded by the conductivity of the earth while the upper half radiates out at the normal rate. I have taken angular measurements indicating this, and others showing the extraordinary and practically unpredictable twists in the field owing to the presence of comparatively small masses of iron. This again points to the unreliability of results obtained with pairs of coils

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placed on board ship unless the screening effects are carefully investigated in each case.

Croydon, Surrey, England, September 17, 1921.

A. Crossley (by letter):* Replying to statements made by Mr. Rivers-Moore, I desire to make the following statements which will clear the mysterious behavior of the two vertical coil collector system observed by him.

First, it may be stated that the writer or his associates have never experienced the contrary results observed by Mr. Rivers-Moore in obtaining the correct location of the cable. The coil nearest the cable always collected maximum power. All persons who were present on board the *Semmes* during the week of October 6, 1920, will bear out the writer in this statement, as it was by means of this pronounced effect that a great many of the persons present actually piloted the *Semmes* over different parts of the course.

A closer inspection of the receiving equipment used by Mr. Rivers-Moore shows that the collector coils used were placed above the deck (unshielded) and in which position the coils would naturally be inoperative with reference to producing marked differences in signal strength. If the coils had been placed over the side of the vessel and sloped outboard at the correct angle the results obtained would be far different than those obtained, as the shielding effect of the vessel would then be brought into play.

The present piloting cable receiving system, described in the PROCEEDINGS OF THE INSTITURE OF RADIO ENGINEERS, volume 10, number 1, is very simple in construction and easy to instal and operate. There are only two switches to operate, one changes the amplifier from the port coil to the starboard coil or vice versa, while the other changes the degree of amplification. In actual practice, the first switch is always used while the second switch is only used for a short while when picking up the cable from seaward. The writer cannot see where the manipulation of a single switch places the apparatus in the complicated class.

The triangular type collector system proposed by Mr. Rivers-Moore may show promising results on wooden or concrete vessels, but most likely would not be practical for use on steel vessels where the electromagnetic field from the cable is distorted by the local structures.

The horizontal coil system is in the same class with the

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triangular collector system and cannot be considered for use on steel vessels, see discussion of the tilting coil system in my article (PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS, volume 9, number 4), on page 288, paragraph 7. The horizontal coil can be adapted for aircraft work, by use of which two maximums can be obtained when in the vicinity of the cable, one to the right and the other to the left of the cable. A discussion of a proposed system for aircraft piloting will be shortly disclosed by me, whereby aircraft can use a system similar to the present ship system for entering airports.

In view of the numerous experiments summarized in my article, I did not go into detail and explain the exact nature of the electromagnetic field in water and above water over the cable, as the curve shown in Figure 9 of my article contained sufficient data to satisfy requirements covering the design of the receiving equipment. I stated, however, that Figures 10 and 11 showed the apparent field acting on the collector coils and the practical results obtained verify the statement. Commenting further on this subject it is known that the field around the cable is bound to be distorted to a certain extent due to the counter action of the field from the inner conductor on the field produce by the return current path thru water and the armor of the cable. The amount of distortion is dependent on the size and resistance of the armor and the water return paths.

It has been proven as the result of extensive experiments conducted to date, that a large size inner conductor with sufficient insulation and a thin armor is the best type of piloting cable. Any increase in the size of the armor greatly detracts from the strength of the received signal from the cable.

Mr. Rivers-Moore refers to the use of a loop of cable for his experiments. The term "loop" is not understood. Does it refer to a straight cable with water return or the usual circular loop with metallic return. If the latter type of insulation was used during his experiments it is understood why Mr. Rivers-Moore obtained results contrary to our results.

Referring to Figures 1 and 2 of his paper, insufficient data on the type of cable used, also length of cable, together with method of grounding the cable makes it extremely hard for the writer to comment on the experimental results represented by the figures. The use of different size of armoring on cables and the method of grounding the internal conductor materially affect the field resulting from the inner conductor and the return path thru water, earth, and the armor. With the original type of

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cable shown in my article, it is possible to obtain signals of 10,000 times audibility, while with a cable that is heavily armored the audibility of the received signal is reduced to 500.

In contrast to the results represented in Mr. Rivers-Moore's figures, the writer, when at New London, used a tilting coil and obtained maximum signals from the cable when the plane of the coil pointed directly at the cable and minimum signals when the plane of the coil was 90 degrees to the cable. The water at New London is brackish and most likely was not of the same degree of salinity as the water in which Mr. Rivers-Moore conducted his experiments.

In concluding it is stated that the negative results obtained with the two vertical coil system by Mr. Rivers-Moore is contrary to the results obtained in this country. Reports received by the United States Hydrographic Office from the British Admiralty during the early part of this year show that the British Admiralty are now using the two coil vertical coil system in the same manner that we do, that is, the coils are placed over the side of the vessel. In view of the Admiralty report, the writer assumes that further experimental work conducted by the Admiralty has corrected the usual oversights made during the initial experiments and that they now make use of the important shielding effect of the hull of the vessel.

For further information on recent work conducted by the British Admiralty, the reader may consult an excellent article on this subject which has been written by Mr. J. J. Bennett, in a recent issue of the London "Electrician." In this article, the results obtained by the Admiralty are described as identical with those observed by the writer and reported in my article.

In answer to Mr. G. W. Pickard's discussion on my paper, I desire to state that the two coil system will not be applicable to cement or wooden ships, and recourse will have to be made to a single coil preferably placed in a horizontal position admidships. Such a coil would give two maximums, one on each side of the cable.

The idea of the use of two cables is theoretically correct if plain insulated cables are used, but such type of cables will not stand up under the abrasive action of moving sands and other destructive agents, as will an armored cable.

It is true that numerous combinations in the form of magnetic fields are possible with the system proposed by Mr. Pickard and it is not unreasonable to think that electrical systems which

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produce certain types of concentrated fields could be used in place of buoys at a later date.

In view of the lengthy discussion which would be necessary in undertaking the discussion of the concentrating effect of the 500 cycle current on the field about the cable, reference should be made to Mr. J. J. Bennett's article on "Leader Cables in Navigation" in the London "Electrician" for August 12, 1921, which very clearly explains this phenomena.

I heartily agree with Mr. Pickard in stating that the art of piloting by means of audio frequency current systems is new, and I predict a wide application of such a system or systems employing supersonic frequencies for all types of mobile bodies.

In answer of Mr. R. H. Marriott's excellent discussion of the piloting cable system, especially his interesting discourse on the troubles to be experienced in introducing and commercializing this new aid to navigation, I wish to congratulate him on his manner of presenting the subject. The Navy Department has gone out of its way to interest pilots and captains of merchant vessels in this system, and in certain cases has loaned apparatus for demonstration purposes; and it is hoped that the outcome of the efforts made to date will lead to greater interest on the part of merchant captains who during peace times can derive the benefits of such a system, to a greater extent than is the case with naval craft.

Mr. Marriott is a pioneer in this art and speaks from experience. The writer fully realizes the great importance of commercializing any new system, especially when it entails an expenditure of a comparatively large sum of money with the thought that no reward is attached to the work involved other than knowing that it will add another aid to the many aids now available to navigators. The great importance of the new system will be appreciated more by navigators of aircraft than navigators of seacraft.

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A NEW RECTIFIER*

By

V. Bush and C. G. Smith

(Research Laboratories, American Radio and Research Corporation)

The purpose of this paper is to introduce to the Institute a new form of rectifier. Briefly described, it consists of a pair of electrodes surrounded by a moderate pressure of gas, the conduction between the electrodes being definitely under the control of a magnetic field. The electrodes may both be cold, as thermionic emission is not utilized. The device has no definite current limit, except such as is imposed by the heating due to losses. It is adapted for high voltage purposes. Its life is very long. In our files it is known as the "S-Tube."

In this present paper, only one of the simplest forms of these tubes will be described, and its theory developed; for a complete analysis is very involved. However, such theory as is here presented can be quite accurately checked with an "S-tube" of the type to which it strictly applies.

Gaseous conduction between electrodes in a gas at low pressure is usually considered an erratic and unreliable phenomenon. When such conduction takes place in a glass tube with widely separated electrodes, the phenomenon decidedly earns its undesirable reputation. The development of this rectifier has been the problem of bringing this conduction under control.

Conduction between widely separated electrodes in a gas at low pressure, assuming that the electrodes remain sufficiently cold to bar effects due to thermionic emission or vaporization of the metal, takes place by reason of ionization by collision. There is always in a gas a certain small amount of spontaneous ionization. Under a potential gradient of sufficient magnitude, the number of ions rapidly increases, for the speed attained by the freed electrons becomes sufficient so that upon impact with neutral molecules they knock them apart, producing ions and more electrons. The process is thus cumulative until sufficient

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current flows to reduce the potential between the electrodes to a definite value, depending upon many factors.

In order to produce gaseous conduction proper, therefore, two factors are necessary: first, a potential gradient sufficient to produce ionization; and second, sufficient distance between electrodes for collision to take place.

If two electrodes are so situated in a gas that they are nowhere separated by a length of discharge path of the order of magnitude of the mean free path of an electron in the gas used and at the pressure present, and if there is no magnetic field present, then there can be no gaseous conduction proper between such electrodes at any potential difference whatsoever. Ionization by collision cannot become cumulative, for in the great majority of cases a spontaneously freed electron drops into the anode without impacting with a neutral molecule. The space between the electrodes is thus kept swept clear of free electrons and ions. The conduction which takes place due to the spontaneous formation of ions is extremely minute, and is the same sort of conduction as takes place between electrodes in air at atmospheric pressure and at potentials below the point of corona formation, which conduction can be with difficulty detected.

It is, in fact, sufficient to prevent conduction that all lines of electrostatic stress between the electrodes be either short compared to the mean free path of the electron, or else be interrupted by an isolated body capable of accumulating a charge. Very many forms of electrodes may be constructed to utilize this principle, one or two of which will be illustrated in this paper.

The tube of Figure 1 will conduct at a comparatively low potential if filled with, say, hydrogen to a pressure of 0.1 mm., even altho the distance of separation a be much less than the mean free path of an electron in hydrogen at this pressure. The conduction will take place along paths such as the one shown dotted.

However, a tube such as shown in Figure 2 will not so conduct; for the only long lines along which an electron may be propelled by the potential difference are interrupted by the glass walls, which will accumulate a charge and reduce the gradient in the gas to a low value.

Such a tube, constructed with properly cleaned electrodes, will not pass a microampere at a potential difference of ten thousand volts. Of course at very high potential gradients, of the order of magnitude of a million volts to the inch, or so, very peculiar effects may be produced; but not gaseous conduction proper.

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A tube which insulates by reason of the short path principle may be rendered conducting by the introduction of a magnetic field of proper value, and in a direction perpendicular to the lines of electrostatic stress.

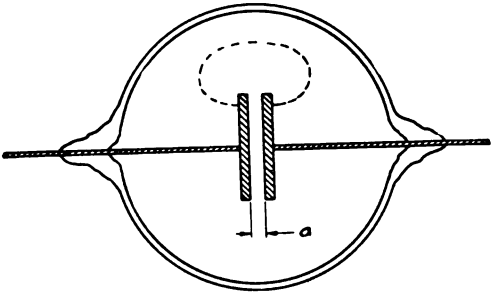

FIGURE 1

When an electron moving in the short distance between two electrodes is acted upon by a magnetic field, its path is curved and thereby lengthened. Moreover, the increase in length of path of an electron starting from the cathode is gradual with increasing magnetic field strength up to a certain value, and then very sudden. This sudden increase occurs when the path curvature is such that the electron completely misses the opposite electrode. The electron paths between plane electrodes for various field strengths are plotted in Figure 3 to render this clear.

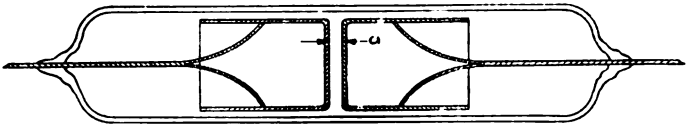

FIGURE 2

The magnetic field strength necessary just to make the electron thus miss the opposite electrode is derived for the plane case in Appendix A. Its value depends upon the potential E between electrodes, their separation a, and the electron ratio of charges to mass m, thus:

$$H = \frac{1}{a}\sqrt{\frac{2Em}{e}} \qquad (1)$$

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or, if E is in volts, and a in cm., we may insert the value of e/m and write:

$$H = \frac{3.35\sqrt{E}}{a} \text{ gausses} \qquad (2)$$

for the critical field strength.

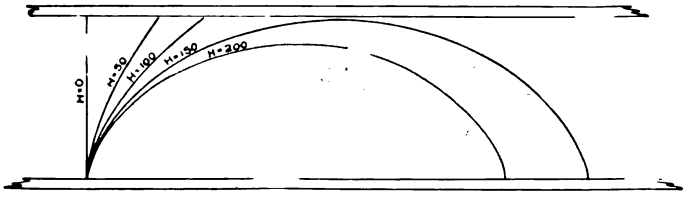

FIGURE 3

Let us now construct a tube such that the distance straight between electrodes is too short to ionize, but such that the path of an electron is just made to miss the opposite electrode is sufficiently long to ionize. Assume a high potential in accordance with the short path principle. Apply a magnetic field to this tube parallel to the electrode surface. Then when this field is increased to the critical value, the tube will very suddenly conduct freely. The electrons fly in long paths and ionize by impact. The positive ions thus formed drop into the cathode and produce secondary emission of electrons from the surface. These new electrons also pursue long paths and ionize, in turn. Since one ion may knock several electrons from the cathode, and each electron may make several ions, the process is cumulative; and the discharge builds up to a point determined by the external circuit.

It may be noted in passing that the critical nature of this phenomenon gives a simple method by which the value of e/m may be checked experimentally.

A rectifier may now be constructed. Construct a short path tube and place it in one of the usual rectifier circuits. Apply to the tube an alternating field and a uni-directional field superposed. Adjust the field such that during one-half cycle it is correct for conduction, and during the next half wave, not. The tube will then rectify completely.

This, however, is not the simplest construction. By using curved electrodes, instead of plane electrodes, a permanent mag-

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net may be used to supply a uni-directional field, and the alternating field dispensed with.

If concentric cylinders are used for electrodes and suitable arrangements made to render the end paths also short, an axial field of proper strength will render the tube conducting. It is shown in Appendix B, however, that the critical field strength is now different for conduction in the two directions. In fact the critical field strengths bear the same ratio as the diameters of the cylinders, that is:

$$\frac{H_h}{H_o} = \frac{g}{h} \tag{3}$$

Thus for conduction with outer cylinder negative, the critical magnetic field is smaller than when the inner is negative.

A tube arranged with cylindrical electrodes and supplied with a permanent axial field, intermediate between these two critical values, will then conduct in one direction but not in the other. This gives a very simple rectifier, indeed.

By suitable choice of diameters and field strength, the tube may be so arranged that it conducts in one direction as soon as the potential across the tube rises to a value sufficient to give ionization by collision and secondary emission, that is to one or two hundred volts depending upon the gas and electrode material used. It may also be arranged so that when the potential in the opposite direction rises to this same value, the field will be already too weak for conduction. The tube will not then conduct in the wrong direction for any value of voltage up to that which destroys the insulation or otherwise flashes the tube over.

Certain other benefits may be obtained by the use of non-uniform fields; but the consideration of these effects will be reserved for later treatment.

A model known as "Type H" is shown in Figure 4, and in Figure 5 as supplied with a permanent magnet and pole pieces for supplying the axial field. A section of this design is also shown in Figure 6.

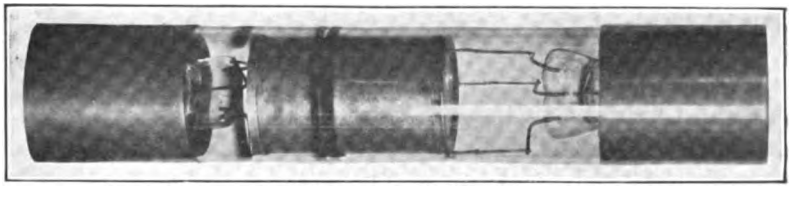

FIGURE 4

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The inert, monatomic gases are preferable for filling "S-tubes," because of their lack of chemical action and low potential drop. Using helium and aluminium electrodes, the drop in the tube is in the neighborhood of 150 volts. Under these conditions the disintegration of the electrodes is very slight when operating normally.

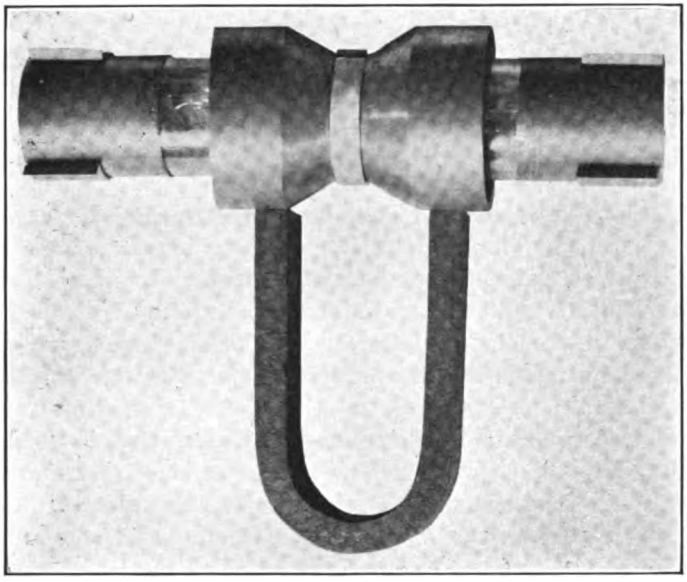

FIGURE 5

Since the cooling of the electrodes occurs largely by reason of the heat conductivity of the working gas, it is unnecessary to run the electrodes very hot in order to dissipate a considerable amount of loss. A tube 7 inches (17.8 cm.) long of the type illustrated above will handle 230 milliamperes continuously with the electrodes well below a red heat. There will then be about 40 watts loss in the tube.

The output depends, of course, on the voltage being rectified. At 4,000 volts a current of 250 milliamperes represents an output of 1 kilowatt. Several amperes may be passed thru such a tube for a short interval.

The voltage current characteristic of a tube depends largely upon its design. With the arrangement shown above the voltage drop will rise about 10 per cent. from no load to full load.

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The wave form of potential delivered by a rectifier depends, of course, upon the circuit in which it is used. The "S-tube" is a complete rectifier, as no appreciable current passes in the reverse direction. A practically constant drop of 150 to 200 volts is inherent in this particular design. By using polyphase connections, or condenser and inductance combinations, the ripple in the delivered voltage may be reduced.

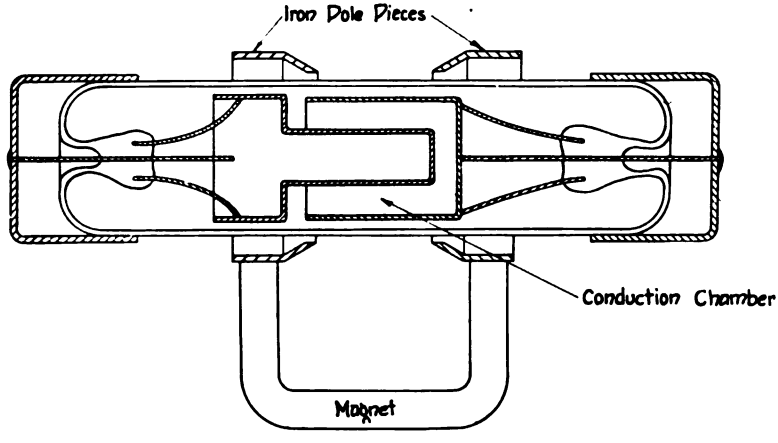

FIGURE 6

As a rugged, long-lived, relatively inexpensive rectifier there will probably be many uses to which the "S-tube" can be put. In particular, it should serve as a convenient source of direct current for use in thermionic tube radio transmitting sets, particularly for high powers. It should make also a convenient piece of laboratory apparatus.

This paper is necessarily limited in its treatment to merely an introduction of the device. The authors will very much welcome any suggestions as to ways in which it will be possible to make this new instrument of greatest service to the practice of radio telegraphy and telephony.

Medford Hillside, Massachusetts,
April 8, 1921.

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APPENDIX A

The Critical Field Strength for Plane Electrodes

The value of the critical field in this case may be found as follows:

Let e = charge on electron
m = mass of electron
X = voltage gradient
H = field strength

Then, referring to Figure 7, we have—

$$m\frac{d^2y}{dt^2} = eX - He\frac{dx}{dt}$$

$$m\frac{d^2x}{dt^2} = He\frac{dy}{dt}$$

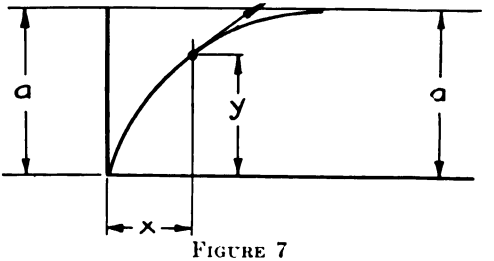

Figure 7

These equations can readily be shown to be those of a cycloid.[1]

Integrating the second equation—

$$m\frac{dx}{dt} = Hey + C$$

Now when $y = 0$, $\frac{dx}{dt} = 0$, and hence $C = 0$,

so that $m\frac{dx}{dt} = Hey$

We are interested, however, in the field strength which will make the path of the electron tangent to the opposite electrode.

If v is the velocity of the electron, we have by the conservation of energy

$$\frac{mv^2}{2} = eXy$$

[1] See Thompson, "Conduction of Electricity Thru Gases."

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$$\text{so that } v = \sqrt{\frac{2eXy}{m}}$$

Now for the path to be tangent, we must have—

$$\frac{dx}{dt} = v$$

$$\text{or } \frac{Hey}{m} = \sqrt{\frac{2eXy}{m}}$$

and, for tangency also, $y = a$, which gives—

$$H = \frac{\sqrt{2}\sqrt{Xa}}{a\sqrt{\frac{e}{m}}}$$

Or, if the potential across the plates is written

$$E = Xa$$

the necessary field strength is

$$H = \frac{\sqrt{2E}}{a\sqrt{\frac{e}{m}}}$$

Inserting the value of e/m, and reducing to practical units—

$$H = \frac{3.35\sqrt{E}}{a}$$

where H is in gausses
E is in volts
a is in cm.

Thus if $a = 0.25$ cm.
$E = 400$ volts

we obtain $H = \frac{(3.35)}{0.25}\sqrt{400} = 268$ gausses

as the necessary field strength.

APPENDIX B

Critical Field Strength for Cylindrical Electrodes

We shall consider first the path of an electron which leaves the inner cylinder, which is considered negative.

Referring to Figure 8, and using the same notation as before—our two equations now become—

$$m\frac{d^2y}{dt^2} = Xe\frac{y}{\rho} + He\frac{dx}{dt}$$

$$m\frac{d^2x}{dt^2} = Xe\frac{x}{\rho} - He\frac{dy}{dt}$$

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From these two equations, eliminating X

$$m\left\{x\frac{d^2y}{dt^2}-y\frac{d^2x}{dt^2}\right\}=He\left\{x\frac{dx}{dt}+y\frac{dy}{dt}\right\}$$

or integrating—

$$x\frac{dy}{dt}-y\frac{dx}{dt}=\frac{He}{2m}(x^2+y^2+C)$$

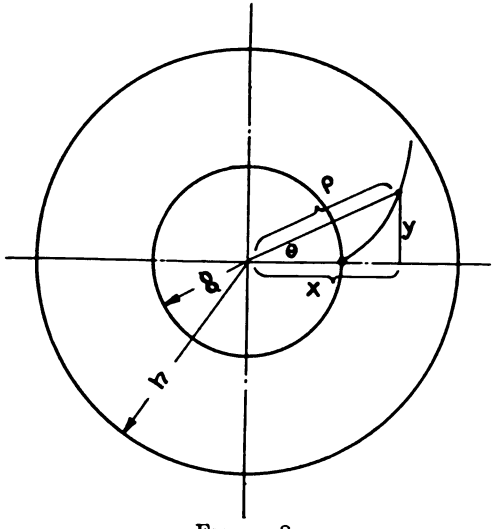

FIGURE 8

and from $y=0,\ \frac{dy}{dt}=0,\ x=g$

we have $C=-g^2$

so that $$x\frac{dy}{dt}-y\frac{dx}{dt}=\frac{He}{2m}(\rho^2-g^2)$$

or, in polar co-ordinates entirely—

$$\rho^2\frac{d\theta}{dt}=\frac{He}{2m}(\rho^2-g^2)$$

$$\frac{d\theta}{dt}=\frac{He}{2m}\cdot\frac{\rho^2-g^2}{\rho^2}$$

For an electron to just reach the other electrode, we have—

$$\frac{mv^2}{2}=eE$$

but here also $$v=h\frac{d\theta}{dt}$$

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which, inserted, give for the necessary field,

$$H_g = \sqrt{\frac{2mE}{e}}\left(\frac{2h}{h^2-g^2}\right)$$

An exactly similar derivation gives for the critical field strength when the outer cylinder is negative—

$$H_h = \sqrt{\frac{2mE}{e}}\,\frac{2g}{h^2-g^2}$$

and dividing we have—

$$\frac{H_h}{H_g} = \frac{h}{g}$$

which equation has been verified many times experimentally.

SUMMARY: The authors describe a new type of cold electrode power rectifier tube utilizing gaseous conduction, and based on the following principles:

No considerable gaseous conduction occurs between coaxial cylindrical electrodes separated by less than the mean free path of the electrons.

An axial magnetic field (perpendicular to the electric force) will cause the electrons to pursue a longer path, and thus permit considerable conduction provided the magnetic field intensity exceeds a critical value.

The critical value of the magnetic field required for producing conduction is greater for conduction from the inner to the outer electrode than in the reverse direction (that is, there are two critical values).

By choosing a magnetic field intensity intermediate between the two critical values, unilateral conductivity results.

Tubes constructed on this basis are described, and their performance given. The approximate mathematical theory of their action is derived.

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POLYPHASE RECTIFICATION*

By

Hudson R. Searing and Mark H. Redmond

The problem of high potential supply for vacuum tube work becomes quite important when large tubes, requiring high voltage, are used. Single-phase alternating current can be rectified, but the resultant direct current is pulsating and seriously distorts the voice when used on a radiophone set, as shown in Figure 1.

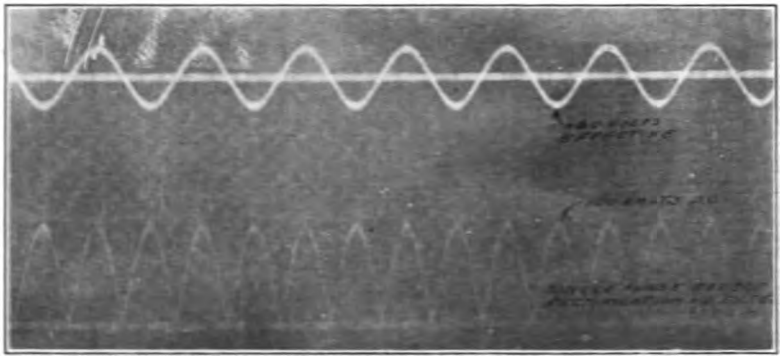

Figure 1

This distortion can be reduced by means of filters (Figure 2), but condensers of large size and high voltage insulation are expensive and bulky.

Experiments were made to determine whether the filters could be dispensed with by using polyphase supply and rectifying each phase. Using three-phase supply with transformers arranged in delta-to-star, and three rectifying tubes, it is possible to secure an output much more desirable than that produced by single-phase operation. The circuit used is shown in Figure 3.

The transformers are connected delta to the supply line and star on the secondary side. Each secondary line is connected

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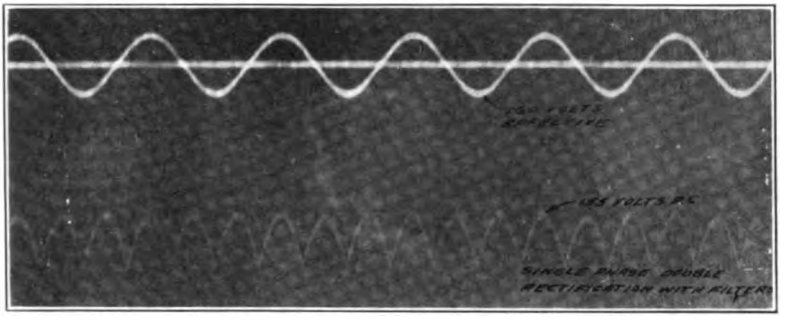

FIGURE 2

to the plate of the rectifier tube, the output being taken from the filament circuit and the neutral of the star connection. The resultant voltage is the envelope of the three-phase waves and

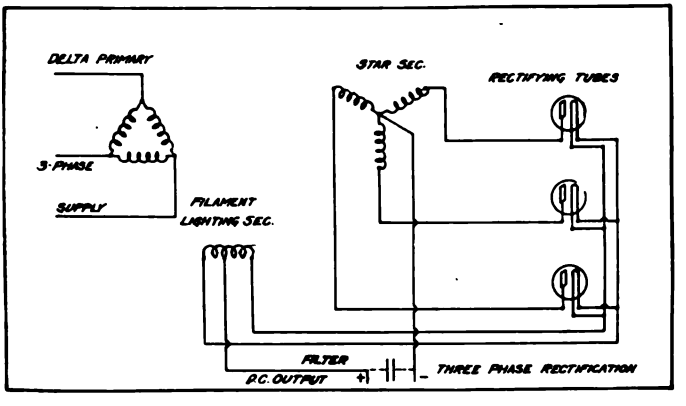

FIGURE 3

consist approximately of an 85 per cent component of direct current plus 15 per cent alternating current of three times the original frequency, and is illustrated in Figure 4. This may be used in radiophone work without serious distortion, but operation is improved by the addition of a filter (Figure 5).

Using six-phase alternating current obtained from a three-phase supply line by the use of transformers connected delta-to-star, an output closely approximating commutated direct current is obtained. This voltage can be used for radiophone work

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without filters with practically no distortion. The circuit is given in Figure 6, while the resulting direct currents, with and without filters, are shown in Figures 7 and 8.

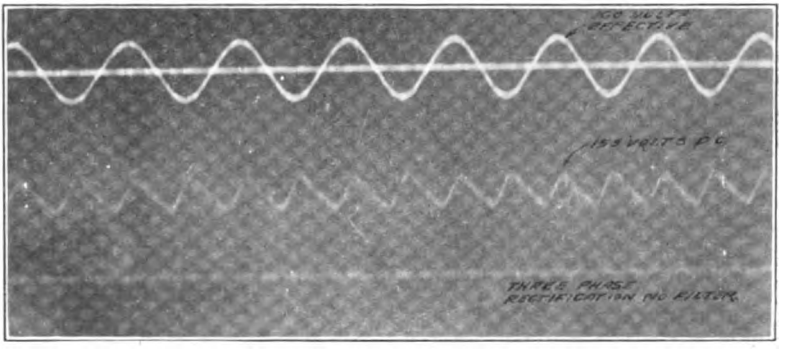

FIGURE 4

In our experiments, Western Electric Company's VT-2 tubes were used, the grid and plate circuits being connected together. When used in this manner, the internal impedance is about 500 ohms. A simple filter consisting of a condenser of 3 microfarads capacity connected across the line was used in the case of those oscillograms marked "with filters."

A polyphase oscillating circuit was tried in which the three- or six-phase voltage was applied to vacuum tubes which were coupled to an oscillating circuit. It was found that more tubes were required for a given output than would have been necessary for rectifier and separate oscillator operation. Furthermore,

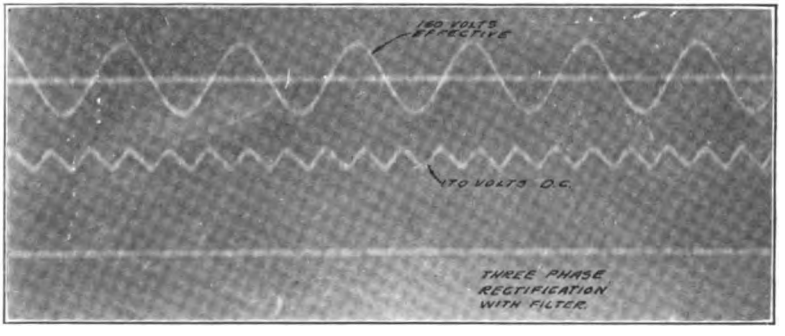

FIGURE 5

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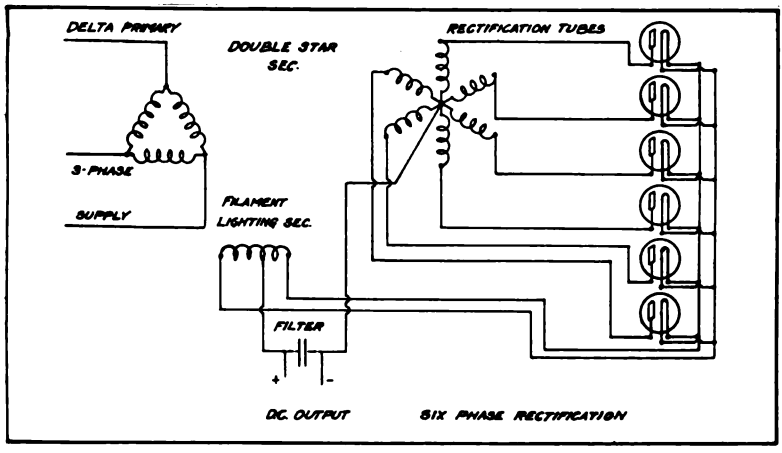

FIGURE 6

modulation by the Heising method was very distorted and unsatisfactory.

At first glance, it would appear that the triple frequency ripple in the three-phase rectified wave would serve as a means to modulate for telegraphy. On account of the limited amplitude of this ripple, such modulation is not sufficient.

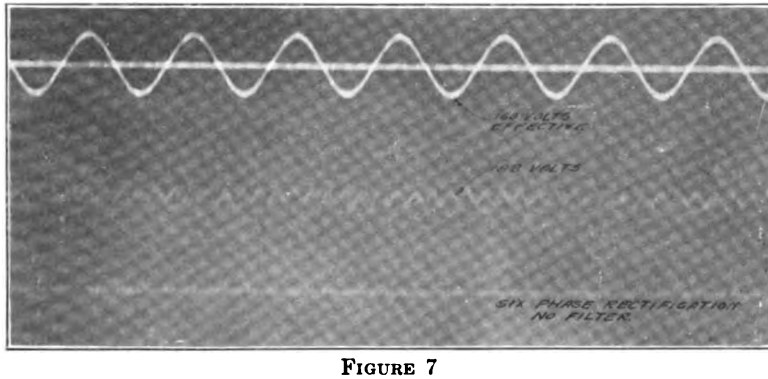

FIGURE 7

The oscillograms were taken in the Research Laboratory of the General Motors Corporation, Delco Section, thru the assistance of Mr. J. H. Hunt, Research Engineer. They show the voltage of one phase and the output. An oscillogram of single-phase rectification is given for comparison.

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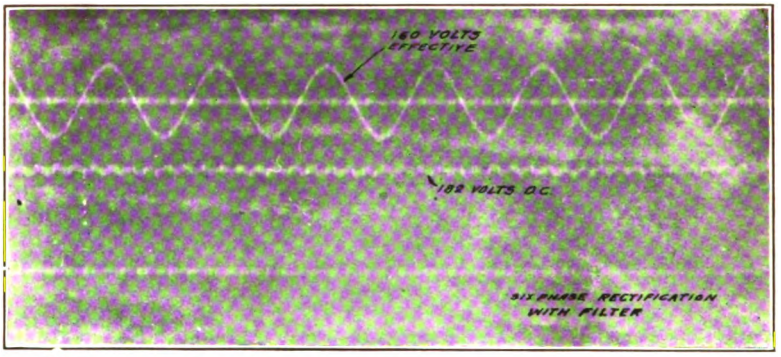

FIGURE 8

SUMMARY: The use of three-phase and six-phase rectified alternating current for feeding the plate circuits of vacuum tube oscillators in radiophone work is described with circuit diagrams and oscillograms of the resulting currents.

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NOTES ON THE THEORY OF MODULATION*

By

John R. Carson

(Department of Development and Research, American Telephone and Telegraph Company, New York)

It is a well-known fact that in carrier wave[1] transmission it is necessary to provide for the efficient transmission and reception not only of the carrier frequency itself but also for a band of frequencies of width depending on the frequency and character of the signal itself. This necessity is becoming more and more a serious consideration as the severity of wave length regulation and the necessity of sharp selective tuning are increased. In view of these facts a great deal of inventive thought has been devoted to the problem of narrowing the band of transmission frequencies. Some of the schemes which are directed to this end are very ingenious; all, however, are believed to involve a fundamental fallacy. It is the purpose of this note to discuss briefly the general problem of modulation and to analyze the more ingenious and plausible schemes which have been advanced to solve this problem.

A pure modulated wave may be mathematically defined by the expression

$$f(t)\, A \cos \omega \qquad (1)$$

Here $f(t)$ is the low frequency signal, $\omega / 2\pi$ is the carrier frequency and A is an amplitude factor which fixes the magnitude of the transmitted wave.

The pure modulated wave is often defined in words as "a carrier wave of constant frequency whose amplitude is proportional to the signal wave." Properly interpreted this definition is correct; however, the inference which is sometimes made, that the *resultant wave* is of constant frequency is erroneous, as may easily be shown.

*Received by the Editor, January 6, 1922.

[1]It is to be understood that the term carrier wave is employed in its generic sense to cover radio as well as carrier wave wire transmission in both of which the carrier wave plays the same role.

[2]See "Carrier Wave Telephony and Telegraphy," by Colpitts and Blackwell, "Journal of the American Institute of Electrical Engineers," April, 1921

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Let the signal wave $f(t)$ be represented, as we assume in telephone theory, by a plurality of sinusoidal terms, thus

$$f(t) = \sum_{1}^{m} a_j \cos(p_j t + \theta_j) \tag{2}$$

Substitution in (1) gives for the pure modulated wave:

$$\begin{aligned} &\frac{1}{2}A \sum_{1}^{m} a_j \cos[(\omega - p_j)\, t - \theta_j] \\ &+ \frac{1}{2}A \sum_{1}^{m} a_j \cos[(\omega + p_j)\, t + \theta_j] \end{aligned} \tag{3}$$

It follows at once that the frequencies transmitted lie between $(\omega + p_m)/2\pi$ and $(\omega - p_m)/2\pi$; that is the width of the bandis $2\, p_m/2\pi$. For example let us take a carrier wave of 100,000 cycles per second, and modulate this wave with telephone signals which we shall assume contain frequencies up to 2,500 cycles per second. The pure modulated wave then contains frequencies lying between 102,500 and 97,500 cycles per second and a band of 5,000 cycles must be transmitted.

It has, however, been known for several years[2] that it is not necessary to transmit the pure modulated wave which contains a band of frequencies of twice the signal wave range of frequencies and that theoretically perfect transmission can be had by transmitting only one "side band" and suppressing the other. This may be explained as follows: Referring to the expression (3) for the pure modulated wave, suppose that all frequencies below[3] that of the carrier $\omega/2\pi$ are filtered out so that the transmitted wave is

$$\frac{1}{2}A \sum a_j \cos(\omega + p_j)\, t + \theta_j \tag{4}$$

Let the receiving stations be provided with a local generator of frequency $\omega/2\pi$ which is combined in the demodulator with the received wave. If the locally generated wave is represented by $B \cos \omega t$, the demodulated wave is

$$\frac{1}{2}A\, B \cos \omega t \sum a_j \cos(\omega + p_j)\, t + \theta_j$$

which is equivalent to

[3]A precisely similar argument holds if all the frequencies *above* the carrier frequency $\omega/2\pi$ are suppressed.

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$$\frac{1}{4}AB\sum a_j \cos(p_j t+\theta_j)$$

$$+\frac{1}{4}AB\sum a_j \cos(2\omega+p_j)\, t+\theta_j$$

The first expression is simply the signal wave $f(t)$ multiplied by the factor $\frac{1}{4}AB$ while the second expression is of double radio frequency which is entirely suppressed in the audio frequency circuits.

In the system of modulation discussed above it will be observed that the *amplitude* of the carrier wave is varied by and in accordance with the low frequencies signal wave and that this process inherently requires the transmission of a band of frequencies at least equal to the range of essential frequencies in the signal itself.[4] In order to eliminate this necessity which is inherent in all actual systems of modulation it has been proposed a number of times to employ an apparently radically different system of modulation which may be termed *frequency* modulation as distinguished from *amplitude* modulation, in the belief that the former system makes possible the transmission of signals by a narrower range of transmitted frequencies. This belief is erroneous; the suggestion is, however, quite ingenious, and the reasoning on which the supposed advantage is based is very plausible, and indeed requires some mathematical analysis before its incorrectness can be satisfactorily established. The system of *frequency* modulation will now be explained and analyzed in terms of the specific physical system in which the idea was first called to the attention of the writer.

Suppose that we have an ideal non-dissipative oscillation circuit of inductance L and capacity C. Such a circuit is of course ideal and unrealizable, but the analysis of the actual vacuum tube oscillator, as regards frequency modulation, may be safely based on a consideration of the ideal circuit. This circuit when once energized, will continue to oscillate at frequency $\omega/2\pi$ when $\omega=1/\sqrt{LC}$. Now suppose that the capacity (or inductance) is varied in accordance with an audio frequency signal. For the present we shall simplify the discussion by assuming that the signal is a pure tone of frequency $p/2\pi$, and that the instantaneous value of the capacity is $C_o(1-2h\ sin\ pt)$ where h is an amplitude factor proportional to the signal intensity. We

[4]It should be noted that after either "side band" is suppressed, the resulting wave does not fall within the definition of a pure modulated wave of equation (1).

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shall later consider the general case where the signal is represented by $f(t)$. Assuming that h is small compared with unity we can write

$$\omega = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{LC_o}}(1+h\sin pt)$$
$$= \omega_o(1+h\sin pt)$$

From the foregoing reasoning it has frequently been concluded that the oscillation circuit generates a continuously varying frequency of instantaneous value

$$\frac{\omega_o}{2\pi}(1+h\sin pt)$$

so that the generated frequency varies between the limits $\omega_o(1-h)/2\pi$ and $\omega_o(1+h)/2\pi$. According to this theory, if $2h\omega_o$ is made less than p the range of frequencies transmitted $2h\omega_o/2\pi$ will be smaller than $p/2\pi$, which is the minimum range required in *amplitude* modulation.

The foregoing gives, very briefly, the essential reasoning underlying the idea of *frequency* modulations. We shall now analyze the scheme more closely: The differential equation of the circuit may be written as

$$L\frac{d^2I}{dt^2} + \frac{1}{C}I = 0$$
$$\frac{d^2I}{dt^2} + \frac{1}{LC_o}(1+2h\sin pt)I = 0 \qquad (5)$$
$$\frac{d^2I}{dt^2} + \omega^2 I = 0$$

Now if ω is treated as a constant, a particular solution is

$$I = A\cos\omega t$$

If we now substitute for ω the expression

$$\frac{1}{\sqrt{LC_o}}(1+h\sin pt) = \omega_o(1+h\sin pt)$$

we get

$$I = A\cos[\omega_o(1+h\sin pt)\,t] \qquad (6)$$

which is interpreted as representing a wave of instantaneous frequency

$$\frac{\omega_o}{2\pi}(1+h\sin pt)$$

Both the solution of the equation and the interpretation of

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this solution are incorrect. Equation (5) by a simple transformation of variables is reducible to the form

$$\frac{d^2 I}{d x^2} + (a + 16\, q \cos x) I = 0$$

which is the canonical form of Mathieu's Equation (see Whittaker and Watson, "Modern Analysis," page 402), and it is easily shown from the theory of this equation that the solution of (5) is *the real part of*

$$e^{i \omega_o t} \sum_{-\infty}^{+\infty} a_n e^{inpt} \tag{7}$$

Consequently the solution is a series of the form

$$\sum_{-\infty}^{+\infty} b_n \cos [(\omega_o + n\, p)\, t + \theta_n] \tag{8}$$

The frequencies present in the wave form an infinite series spaced at the interval $p/2\pi$ of the signal frequency. They may be tabulated as

	ω_o	
$\omega_o + p$		$\omega_o - p$
$\omega_o + 2\, p$		$\omega_o - 2\, p$
$\omega_o + 3\, p$		$\omega_o - 3\, p$
. . . . .		. . . . .
$\omega_o + n\, p$		$\omega_o - n\, p$

It follows at once that *the transmission of the signal by frequency modulation requires the transmission of a band of frequencies* at least $2p/2\pi$ *in width*; that is *a band of width equal to twice that of the signal itself.*

If the solution (7) is substituted in the differential equation (5), we get the following system of difference equations for the determination of the constants.

$$-i\,(2\, n\, p\, \omega_o + n^2 p^2)\, a_n + h\, \omega_o^2 (a_{n-1} - a_{n+1}) = 0 \tag{9}$$

In the practically important case where p is so small compared with ω_o that np may be neglected in comparison with ω_o, this is satisfied by

$$A_n = (i)^{-n} J_n\, (h\, \omega_o / p) \tag{10}$$

where $J_n\, (h\, \omega_o / p)$ is the Bessel function of order n and argument $h\, \omega_o / p$. In this case the series sums up to

$$I = A \cos \left(\omega_o t - \frac{h\, \omega_o}{p} \cos pt \right) \tag{11}$$

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The ratio of the term of frequency $(_o\omega+p)$ to the fundamental of frequency ω_o is $J_1(h\omega_o/p)/J_o(h\omega_o/p)$, which in case $h\omega_o/p$ is less than unity is approximately equal to $h\omega/2p$. This system of modulation, therefore, discriminates against high frequencies and therefore inherently introduces distortion.

In analyzing this system of frequency modulation consideration has been limited to the case of a signal consisting of a pure tone of frequency $p/2\pi$. In the more general case where the signal must be represented by an arbitrary $f(t)$, as is the case in telephonic transmission, a general solution can only be gotten when $f(t)$ is periodic and analyzable into a Fourier series. In this case the differential equation of the problem is reducible to Hill's equation (Whittaker and Watson, "Modern Analysis," page 406), and the theory of this equation shows that the frequencies present in the wave are exactly the same as those given above if $p/2\pi$ is the fundamental frequency of $f(t)$.

However if we introduce the approximations indicated by physical considerations, a much simpler and more instructive approximate solution is obtainable without analyzing $f(t)$. Let the instantaneous capacity be represented by $C_o(1-2hf(t))$; then assuming $2hf(t)$ small compared with unity the differential equation of the problem is

$$\frac{d^2I}{dt^2}+\omega_o^2(1+2hf(t))I=0$$

Assuming that the solution is the real part of $e^{i\omega_o t}\phi(t)$ and substituting in the differential equation we get

$$i2\omega_o\phi'(t)+\phi(t)+2h\omega_o^2 f(t)\phi(t)=0.$$

Now if $f(t)$ is a relatively slowly varying function compared with the carrier wave, the term $\phi''(t)$ may be neglected and we get

$$\phi(t)=Ae^{i\omega_o h\int f(t)dt}$$

whence

$$I=A\cos[\omega_o(t+h\int f(t)\,dt)] \qquad (12)$$

If $\omega_o h\int f(t)\,dt$ is small compared with unity, as it would be in practice, this gives approximately

$$I=A\cos\omega_o t-\omega_o hA\int f(t)\,dt\sin\omega_o t$$

The second term is a modulated wave, but the amplitude instead of being proportional to the signal wave is proportional to its integral. Consequently this type of modulation inherently distorts without any compensating advantages whatsoever.

The foregoing solutions, tho unquestionably mathematically

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correct, are somewhat difficult to reconcile with our physical intuitions, and our physical concepts of such "variable frequency" mechanisms as, for example, the siren. Upon closer analysis it is seen, however that the difficulty arises in connection with what we mean by frequency, and can be cleared up satisfactorily, it is believed, by the following generalized concept and definition of frequency.

Suppose we have a function $sin(\Omega(t))$ where $\Omega(t)$ is any specified function of time: Its derivative with respect to time is $\Omega'(t)\cos\Omega(t)$ where $\Omega'(t)=d/dt\Omega(t)$. We define the *generalized frequency* of such a function as equal to $\frac{1}{2\pi}\Omega'(t)$. This definition, while formally arbitrary, has considerable physical significance, and is believed to be a useful concept. In the case where $\Omega(t)=\omega t$ it agrees with the usual definition of frequency $\omega/2\pi$. Furthermore, if we apply this definition to formulas (11) and (12) the *generalized frequencies* are respectively $\omega_o(1+h\sin pt)$ and $\omega_o(1+hf(t))$, which agree with our physical intuitions. It agrees also with the fact that in the case of the siren the mathematical analysis of which differs in no essential way from that of the "variable frequency" oscillator just discussed, the *generalized frequency*, as defined above, corresponds with the "instantaneous frequency" which the ear apperceives. This may be shown as follows:

In the neighborhood of time $t=\tau$, $\Omega(t)$ may be expanded as

$$\Omega(t)=\Omega(\tau)+\frac{t-\tau}{1!}\Omega'(\tau)+\frac{(t-\tau)^2}{2!}\Omega''(\tau)+\cdots$$

Now the function $sin[\Omega(t)]$ alternates when the function $\Omega(t)$ changes by the amount π; or otherwise stated, the interval between zeros corresponds to the time intervals during which $\Omega(t)$ changes by the amount π. From the foregoing expansion this interval is approximately $\pi/\Omega'(t)$ in the neighborhood of the time $t=\tau$. That is to say, *the rate of alternation of the function* $sin[\Omega(t)]$ is approximately *the same at any time t, as that of the function* $sin\,\omega t$, *where* $\omega=\Omega'(t)$. In this sense and this sense only do "variable frequency mechanisms" generate a continously varying frequency over the range of frequencies corresponding to the extreme values of $\Omega'(t)$.

Exactly the same conclusions are reached by the analysis of another theoretically possible scheme of frequency modulation which suggests itself. This is to vary the speed of a radio frequency alternator in accordance with the signal so that its in-

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stantaneous angular velocity is representable by

$$\omega(1+hf(t))$$

A superficial consideration of this scheme would lead to the erroneous conclusion that the frequency generated is

$\frac{\omega}{2\pi}(1+hf(t))$ and for a sinusoidal signal varies between $\frac{\omega}{2\pi}(1-h)$ and $\frac{\omega}{2\pi}(1+h)$. A mathematical analysis shows, however, that it differs in no essential way from the arrangement analyzed above and that the frequency band which must be transmitted is at least equal to that required in *amplitude* modulation.

The foregoing discussion is immediately applicable to the analysis of the system of continuous wave radio telegraphy which employs the so-called "spacing wave." In its essentials this system merely employs "frequency modulation" instead of "amplitude modulation" in the sense employed above and formula (12) is directly applicable. It follows therefore at best, as regards the necessary range of frequencies, the "spacing wave" system is inferior to that in which the dot and dash correspond to modulation of amplitude of a constant frequency carrier. Superiority, however, has been claimed for the former on the alleged ground that, since "the amplitude is constant," transient disturbances are minimized. This claim is seen to be quite invalid when the real significance of "frequency modulation" is analyzed, and no such superiority exists.

SUMMARY: The transmission system of "frequency modulation" (transmission by variation of the frequency of the radiated wave) is mathematically analyzed, and the width of the band of frequencies occupied by this method of transmission at a given speed is compared with the width of the corresponding band for transmission by amplitude variation. It is proved that the frequency modulation system using a spacing or compensating wave is inferior to the amplitude variation system both as to the width of the frequency band occupied and as to distortion of signal wave form.

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DIGEST OF UNITED STATES PATENTS RELATING TO RADIO TELEGRAPHY AND TELEPHONY*

ISSUED NOVEMBER 1, 1921–DECEMBER 27, 1921

BY

JOHN B. BRADY

(PATENT LAWYER, OURAY BUILDING, WASHINGTON, D. C.)

1,395,378—Richard H. Wilson, of Newark, New Jersey and John P. Schafer, of Richmond Hill, New York, filed September 29, 1919, issued November 1, 1921. Assigned to Western Electric Company.

SECRET SIGNALING. This patent shows a radio telephone secret signaling system. The transmitter comprises two branch circuits and separate modulators coupled thereto. The microphone circuit is coupled to filter circuits which transmit freely only a limited range of the essential voice frequencies. For example, one filter may transmit frequencies between 500 and about 900, while the other filter will transmit frequencies between 900 and about 1,500. Separate carrier wave frequencies may be employed from separate generators modulated in accordance with the separate modulators actuated by the frequencies transmitted through the filters. At the receiving station branch circuits are employed to combine the component frequencies forming the signal wave. An outsider in attempting to pick up the conversation would tune his receiving set to the frequency of one or the other of the transmitted carrier waves, but would obtain only unintelligible sounds from either wave alone.

1,395,390—Lewis M. Clement, of Newark, New Jersey, issued November 1, 1921, filed September 30, 1918. Assigned to Western Electric Company.

OSCILLATION-GENERATING SYSTEM. The object of this invention is to provide a vacuum transmitter with means for varying the frequency of the oscillator and simultaneously to automatically

*Received by the Editor, January 5, 1922. The purpose and scope of this section of the PROCEEDINGS have been given in previous issues, and will not be repeated herein.

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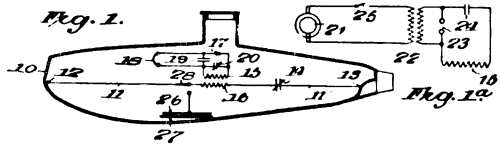
provide the proper plate coupling and feed-back coupling for any particular frequency at which the oscillator is set to operate. A number of different wave lengths are made available, and the operator can switch from one to the other instantly. No adjustment need be made other than a single movement of a single switch.

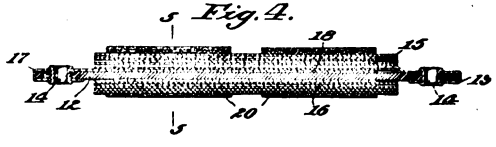
1,395,454—James Harris Rogers, of Hayattsville, Maryland, filed March 9, 1920, renewed September 12, 1921, issued November 1, 1921.



NUMBER 1,395,454—Radio Signaling System

RADIO SIGNALING SYSTEM. This patent shows an antenna for a submarine vessel having a metallic hull comprising conductors extending longitudinally and entirely inclosed by the hull and electrically connected at their ends to the metallic walls of the hull. The radio signaling apparatus is inductively coupled to this antenna system. A modification of the system shows a loop antenna contained entirely within the metallic hull of the submarine.

1,395,931—Charles F. Smith and William H. Smith, of Brooklyn, New York, filed May 17, 1920, issued November 1, 1921.



NUMBER 1,395,931—Electric Condenser

ELECTRIC CONDENSER. An electric condenser unit is shown in this patent comprising a base or body of thin board and a wrapping of dielectric and metallic foil encircling the fiber board. The sheets of metal foil are smaller in size than the sheets of dielectric and the stack is folded around the fiber board and the leads brought out to eyelet terminals on the ends of the board.

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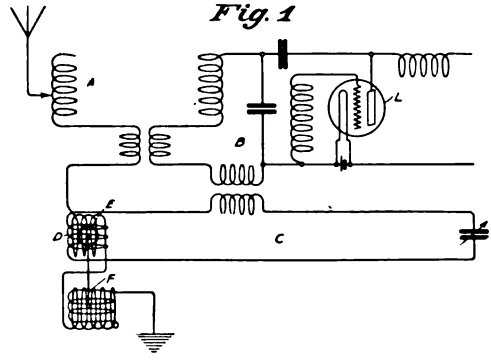
A number of units may be associated in parallel by building up a structure with bolts passing thru the eyelet terminals.

1,395,987—Henry Joseph Round, of London, England, filed March 24, 1921, issued November 1, 1921. Assigned to Radio Corporation of America.



NUMBER 1,395,987—"Wireless" Signaling Apparatus

"WIRELESS" SIGNALING APPARATUS. The object of this invention is to provide means whereby the wave length of a radio transmitter may be kept constant automatically. The antenna circuit and the closed oscillator circuit of the transmitter are combined with a small rotating field motor comprising two windings. One winding is connected in the closed circuit and the other winding in the antenna circuit or in any circuit whose period varies with that of the antenna. When the antenna is exactly in tune with the closed circuit there will be no rotating field produced by the two windings at right angles; but if the antenna increases its wave length, the phase of the antenna current will tend to produce a rotating field in one direction whereas if the antenna decreases its wave length the rotating field will be in the other direction. The rotation of the shaft of the armature of the rotating field motor controls a variometer, a variable condenser, or other means for varying the period of the antenna. Thus when the antenna increases its wave length the variometer decreases it until there is no longer any rotating field and vice versa, so that the wave length of the antenna is kept practically constant. The system is intended for all types of sets such as a vacuum tube transmitter, an alternator, or an arc transmitter.

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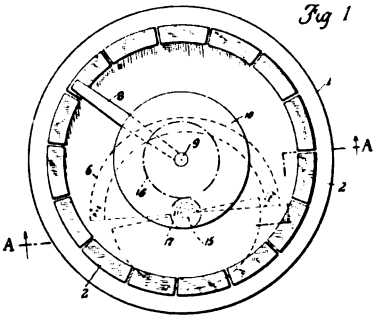
1,396,030—William Dubilier, of New York, N. Y., filed July 25, 1917, renewed February 2, 1921, issued November 8, 1921.



NUMBER 1,396,030—Variable Condenser

VARIABLE CONDENSER. A variable condenser is shown in this patent comprising a number of fixed condenser units connected to contacts, a switch for cutting in the units, and variable condenser having a maximum capacity substantially equal to the common difference between the capacities of the fixed condenser units. Intermediate capacities between the fixed capacities are thereby obtained by manipulating the variable condenser while the errors due to changes in the variable condenser are minimized.

1,396,491—R. L. Williams, of Newton, Massachusetts, filed June 24, 1919, issued November 8, 1921. Assigned to Submarine Signal Company.

DEVICE FOR ESTIMATING DISTANCES. This patent shows a combination radio system and submarine sound signal system wherein a radio transmitter is operated to give a single signal simultaneously with the operation of a submarine sound signal. The operator at the receiving station gets the single instantaneous radio signal and later hears the first blow of the submarine signal and by measuring the time between the receipt of the radio signal and the first blow of the submarine signal can calculate the distance from the transmitting station.

1,396,571—Alfred N. Goldsmith and Julius Weinberger, of New York, N. Y., filed September 13, 1918, issued November 8, 1921. Assigned to General Electric Company.

RADIO RECEIVING SYSTEM. The object of this invention is to provide a receiving system which is adapted to be used in close

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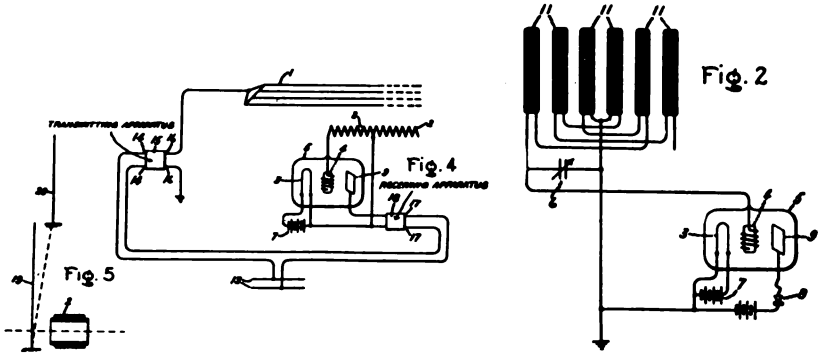
proximity to a transmitting system and which is capable of receiving signals from a distant station at the same time that signals are being sent from the transmitting station. In the diagrams, the transmitting antenna is indicated by 1, and 2 is the coil employed for reception. This coil is connected to the cathode 3, and grid 4 of an electron discharge amplifier 5. A tuning condenser 6 may be used for tuning the receiving circuit to the frequency of the signals to be received. The plate cir-



NUMBER 1,396,571—Radio Receiving System

cuit of the amplifier 5 comprises the cathode 3 of the amplifier, a local source of current 7, a wave responsive device 8, and the anode 9 of the amplifier. The grid 4 is connected to one end of the coil 2 and the cathode 3 is connected to the junction point of the two halves of the coil. This point is connected to earth. The mode of operation of this system may be explained as follows: The exposure of the two halves of coil 2 may be represented by condensers between the antenna and the coil. It will be apparent that, for currents flowing thru these condensers and the two halves of coil 2 to ground, the magnetic field of the two halves are in opposition and the two halves of coil 2 act as inductances in parallel. The inductance of the coil for such currents then is $\frac{L-M}{2}$ where L is the inductance of each half of the coil and M is the mutual inductance between the two halves. If M is made equal or very nearly equal to L, then the coil becomes a non-inductive path to ground for capacitively induced currents; consequently no potential difference can build up across its terminals and no interference will result in the receiving set from the local antenna.

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1,396,745—Arthur Haddock, of East Orange, New Jersey, filed May 19, 1919, issued November 15, 1921. Assigned to Western Electric Company, Inc.

Vacuum Tube Circuits. This patent relates to a multistage amplifier. Switching means are provided for varying the number of effective tubes between the input and output circuit of the amplifier and also for regulating the potential between the incoming line and one of the tubes. The object of the circuit is to vary the amplification to any desired degree between the input circuit and the output circuit.

1,396,786—E. O. Scriven, of New York, N. Y., filed November 6, 1916, issued November 15, 1921. Assigned to Western Electric Company, Inc.

System for Transmission of Intelligence. This invention relates to a radio telephone system wherein signals are transmitted or received by means of a high frequency carrier wave modulated in accordance with the signals. The circuit embodies the combination of two vacuum oscillators which serve as a source of high frequency carrier wave oscillations, the impedance of which combination is varied according to the low frequency signals to be trasnmitted. At the receiver a vacuum tube containing two grids, two plates, with common filament is employed. The circuit may be arranged for either high frequency carrier wave reception or modulated high frequency wave reception, in which latter case the tube serves as a homodyne generator, that is, it should produce oscillations of the same frequency as the incoming high frequency oscillations. If the incoming waves are not modulated the vacuum tube generator should be a heterodyne generator, that is, it should generate oscillations of a frequency different from that of the incoming carrier waves to produce a frequency within the limits of audition.

1,396,897—Phillips Thomas, of Edgewood Park, Pennsylvania, filed October 8, 1917, issued November 15, 1921. Assigned to Westinghouse Electric and Manufacturing Company.

Condenser. This patent shows a construction of condenser having means for filing the space which remains at the edges of the conducting foils in condensers constructed in the usual manner. A U-shaped strip of dielectric material is cut to fit closely around the margin of a conducting foil, the strip being substantially of the same thickness as the foil. The conducting

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sheets assembled with the U-shaped strips are stacked with intermediate sheets with one side of the conducting sheet extending to form the terminals of the condenser.

1,397,093—Lloyd Espenschied, of Hollis, New York, filed September 27, 1919, issued November 15, 1921. Assigned to American Telephone and Telegraph Company.

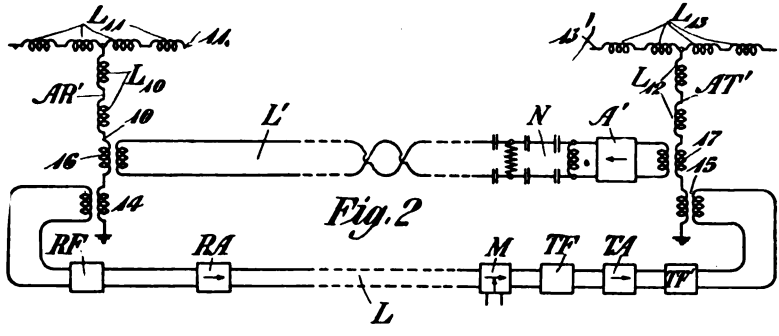

Fig. 2

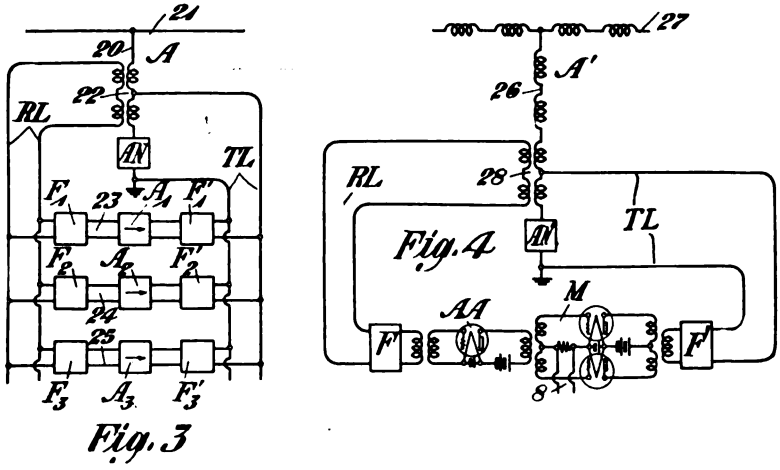

Fig. 3

Fig. 4

NUMBER 1,397,093—Radio Repeating System

RADIO REPEATING SYSTEM. This invention relates to radio repeating stations and apparatus for amplifying at intermediate points the signals transmitted between two terminal stations.

1,397,432—Charles V. Logwood, of New York, N. Y., filed June 16, 1917, issued November 15, 1921.

SIGNALING SYSTEM. This patent relates to a radio trans-

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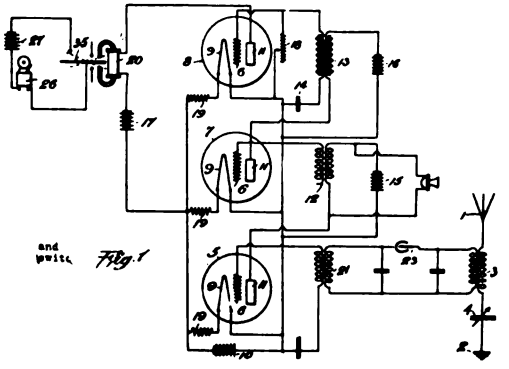
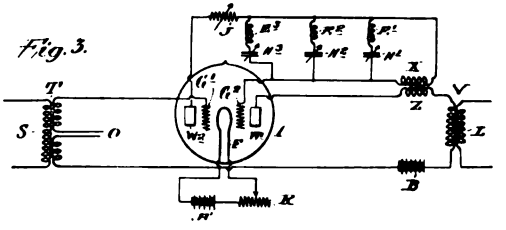
mitting and receiving vacuum tube apparatus with means for automatically switching from transmitting to receiving.



NUMBER 1,397,432—Signaling System

1,397,575—L. De Forest, of New York, N. Y., filed April 9, 1915, issued November 22, 1921. Assigned to De Forest Radio Telephone and Telegraph Company.



NUMBER 1,397,575—Selective Audion Amplifier

SELECTIVE AUDION AMPLIFIER. This patent describes a vacuum tube amplifier having in its output circuit a plurality of oscillating circuits associated therewith to amplify impressed currents of certain input frequencies to a greater degree than impressed currents of other frequencies.

1,397,862—Albert L. Fitch, of East Orange, New Jersey, filed November 26, 1917, renewed December 26, 1918, issued November 22, 1921. Assigned to Western Electric Company, Inc.

TRANSMISSION SYSTEM. This invention relates to a radio telephone modulating circuit employing a condenser transmitter connected to a vacuum tube amplifier and using a single battery

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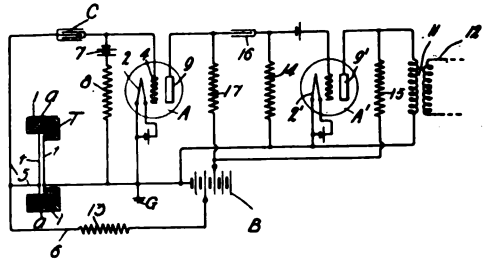
both in the output circuit of the amplifier, and as a means for polarizing the transmitter. In the usual operation of a vacuum tube amplifier circuit with condenser telephone employing a single battery as described, the filament is usually grounded and accidental grounding of the condenser transmitter case causes either the battery or the condenser transmitter to be short-circuited and thus interferes with the operation. The present

Fig. 2.



NUMBER 1,397,862—Transmission System

invention remedies this defect by connecting the battery to perform both the functions of charging the condenser transmitter and furnishing current to the output circuit in the amplifier circuit such that one electrode of the condenser transmitter is always grounded and the other electrode is arranged to make grounding substantially impossible. The source of electromotive force is common to both the circuits thru the condenser transmitter and the output circuit of the vacuum tube amplifier as shown in the diagram.

1,398,848—James Erskine-Murray and James Robinson, of Biggin Hill, England, filed March 30, 1920, issued November 29, 1921.

"WIRELESS" RECEIVING AND TRANSMITTING APPARATUS. This patent shows a radio transmitting and receiving system wherein a receiving station determines its bearing relatively to the transmitting station. The transmitting apparatus employs a plurality of antennas arranged in different directions. The receiving station employs an antenna having branch circuits to ground which are alternately connected in the antenna circuit. Two identical coils *c* and *d* are included in the branch circuits and arranged at an angle with each other. An adjustable receiving inductance *e* is coupled with the two circuits and ad-

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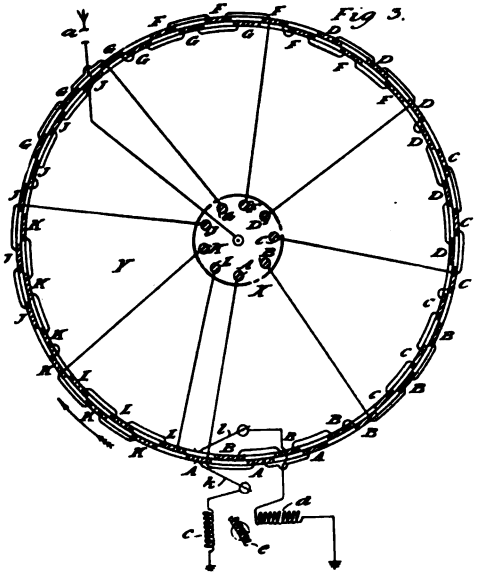
justed for comparison of the received signals which permits a bearing to be obtained on the distant transmitting station on minimum signals.



NUMBER 1,398,848—"Wireless" Receiving and Transmitting Apparatus

Re 15,241—Albert Pruessman, of East Orange, New Jersey, application for reissue filed June 14, 1920, reissued November 29, 1921. Assigned to Western Electric Company.

CONDENSER AND METHOD OF MAKING THE SAME. This patent relates to a method of treating a condenser which is impregnated in the presence of heat, which consists in applying pressure to the impregnated condenser as it cools and then removing the pressure, reheating the condenser to a temperature of not less less than 120 degrees F. for a period of not less than three hours without pressure applied thereto.

1,399,005—G. B. Crouse, of Brooklyn, New York, filed June 14, 1918, issued December 6, 1921. Assigned to The Sperry Gyroscope Company.

SPARK-GAP. This invention relates to a spark-gap construction for a buzzer transmitter, operated from a direct current source. The spark-gap construction comprises a vibratory electrode, a portion thereof being magnetic material whereby the

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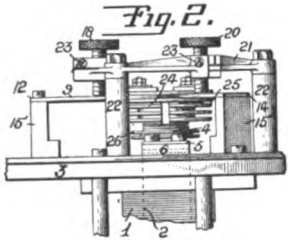
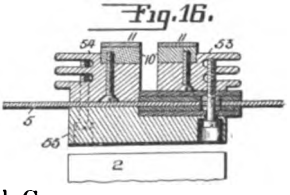
electrode may be vibrated by energizing an adjacent electromagnet. A plurality of insulated electrodes are arranged to be normally bridged across the vibratory electrode. Signals are produced upon closing of a key, causing vibratory action of the spark-gap electrode.





NUMBER 1,399,005—Spark-Gap

1,399,251—Emory Leon Chaffee, of Belmont, Massachusetts, filed July 31, 1917, renewed April 21, 1921, issued December 6, 1921.

MEANS FOR CHANGING THE INTENSITY OF SIGNALS IN RADIO-DYNAMIC RECEIVING SYSTEMS. This patent shows a circuit for the reduction of the intensity of strong signals in radio-dynamic control work without reducing the intensity of weak signals. The object of the invention is to reduce interference in radio-dynamic control circuits from nearby transmitters and from static.

1,399,254—John Hays Hammond, Jr., of Gloucester, Massachusetts, filed June 30, 1917, renewed April 20, 1921, issued December 6, 1921.

SYSTEM OF RADIO-DYNAMIC CONTROL. This patent shows a radio transmitter control circuit for use in a system of radio-dynamic control for torpedoes and the like. The transmitter includes two sets, one being intended to transmit different wave lengths thru any desired variable range to disturb the enemy, and other being provided with a plurality of control circuits, whereby the frequency transmitter may be changed over a series of wave lengths to control the distant object.

1,399,945—Harold F. Elliott, of Palo Alto, California, filed July 24, 1920, issued December 13, 1921. Assigned to Augustus Taylor.

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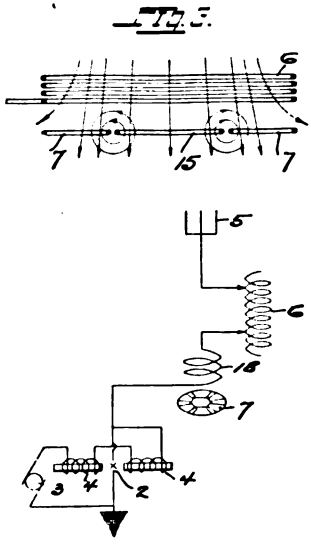

FIG. 5.

NUMBER 1,399,945—Radio Telegraphy

RADIO TELEGRAPHY. This patent relates to a high power arc signaling system in which the signals are produced by a variation in wave length of the radiated wave. The antenna inductance is changed to produce the signals by the closing of a plurality of pairs of contacts in a system of loops inductively associated with the antenna inductance. The shorting inductance includes a plurality of separate loop circuits concentric with the axis of the antenna inductance and each opened and closed simultaneously by a pair of contacts electromagnetically controlled by a signaling key.

1,400,235—John H. Payne, Jr., of Schenectady, New York, filed September 14, 1916, issued December 13, 1921. Assigned to General Electric Company.

METHOD OF AND MEANS FOR PRODUCING ALTERNATING CURRENTS. This patent shows a vacuum tube circuit for the production of alternating currents. The coupling between the grid and the plate circuits is provided by condensers. Inductances in the grid and plate circuits and the capacities therein are preferably so chosen that radio frequency oscillations will be set up in the circuit which includes these inductances and capacities. The frequency of these oscillations may be varied by

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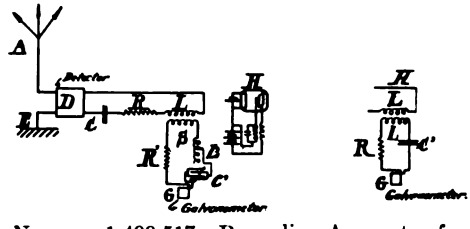
changing the position of the plates of a condenser shunting the grid and plate circuits. The inductances and condensers in associated circuits are so proportioned that the circuit including these inductances and capacities will be resonant to a different and preferably an audible frequency, and the frequency of the alternating currents generated in this circuit may be varied by varying the capacity therein.

1,400,847—Ernst F. W. Alexanderson, of Schenectady, New York, filed December 31, 1918, issued December 20, 1921. Assigned to General Electric Company.

SYSTEM OF RADIO COMMUNICATION. This patent shows a speed regulating mechanism for a radio frequency alternator employed at the transmitter in a radio system. The radio frequency alternator shown in the drawings is driven by a three-phase electric motor supplied with power from a distribution system, and a regulator relay is employed to control the power delivered to the shaft of the alternator. The regulator comprises a tuned circuit energized by current derived from the high frequency alternator. A rectifier is associated with the tuned circuit and delivers rectified current to the relay for controlling the power to the motor. Various means are described for amplifying the variations of energy acting upon the regulator relay whereby great sensitivity is obtained to maintain constant the speed of the alternator.

1,400,517—André Eugene Blondel, of Paris, France, filed April 26, 1919, issued December 20, 1921.



NUMBER 1,400,517—Recording Apparatus for Radiotelegraphic Signals

RECORDING APPARATUS FOR RADIOTELEGRAPHIC SIGNALS. This patent shows a galvanometer or oscillograph which is adjusted to resonance with an alternating current of any given frequency. The circuit employed includes a receiving antenna

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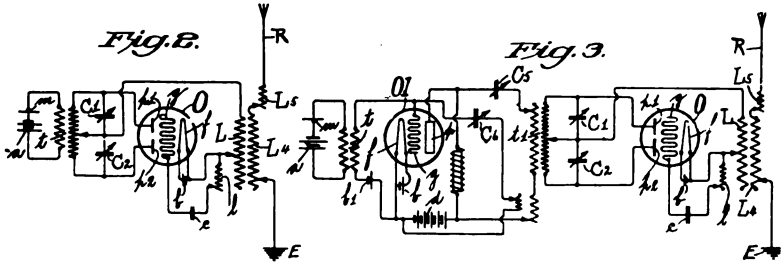
system, a detector and a vibrating galvanometer connected in a low resistance tuned circuit. The galvanometer winding may operate the usual mirror for oscillograph reception.

1,400,591—Cornelius D. Ehret, of Philadelphia, Pennsylvania, filed March 12, 1919, issued December 20, 1921.



NUMBER 1,400,591—Electrical Wave Transmission

ELECTRICAL WAVE TRANSMISSION. This invention relates to the transmission of radio telephone signals wherein high frequency oscillations are not existent or produced except when the microphone is actuated. The oscillator employed in the system includes a pair of anode circuits, a heated cathode, and a grid circuit. An amplifier may be inserted between the microphone circuit and the oscillator and between the oscillator and the antenna radiating system. In the operation of the system, Figure 3, modulating energy is impressed by transformer t_1 upon the anode circuits of the oscillator O with the result that all of the frequencies of positive polarity are converted by one of the anode circuits while all of the frequencies of negative polarity are converted by the other of the anode circuits. Thus, there are directly produced, by conversion of the amplified telephonic energy, high frequency oscillation varying in amplitude in accordance with speech waves. The telephonic energy is the only energy supplied to the plate or anode circuits as distinguished from systems wherein a battery supplies the anode circuit and wherein only the telephonic energy is employed merely to vary the potential of the grid of the oscillator.

1,401,121—Roy M. Allen, of East Orange, New Jersey, filed May 24, 1918, issued December 27, 1921. Assigned to Western Electric Company, Inc.

MOUNTING FOR VACUUM TUBES. This invention relates to a

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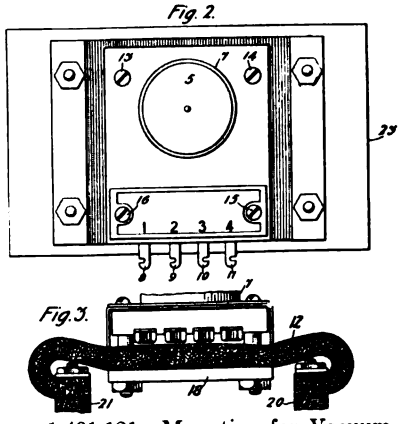
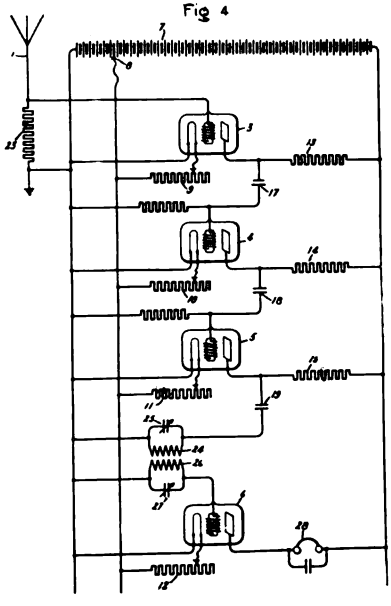


NUMBER 1,401,121—Mounting for Vacuum-Tubes

resilient support for vacuum tubes to reduce the effect of an external vibration upon the structure of the tube.

1,401,644—Chester W. Rice, of Schenectady, New York, filed July 31, 1917, issued December 27, 1921. Assigned to General Electric Company.



NUMBER 1,401,644—Method of and Apparatus for Amplification of Small Currents

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Method of and Apparatus for Amplification of Small Currents. The amplifier shown in this patent employs a plurality of vacuum tubes in which all of the plate circuits are supplied with current from a common source and a high resistance is applied to the grid circuit of the first amplifier of the series and the current in the plate circuit of that amplifier is varied proportionally. As a result there will be a variation in potential difference between the cathode and anode of the amplifier and this variable potential is applied to the grid circuit of the second amplifier. The variable potential between cathode and anode of the second amplifier is in turn applied to the grid circuit of the third amplifier and so on thruout the series. The plate circuit of the last amplifier includes a telephone receiver or other device for detecting the received signals.

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THE PIEZO-ELECTRIC RESONATOR*

By

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In the course of experiments with piezo-electric crystals, extending over a number of years, certain radio frequency phenomena were brought to light, the practical application of which appeared worthy of development. The two applications that seem most promising at present are (1) as a frequency-standard, and (2) as a frequency-stabilizer, or means of generating electric oscillations of very constant frequency. It is with these that this paper is chiefly concerned. The fundamental phenomena will first be described, followed by the mathematical theory, and finally an account of the applications will be given.[1]

I. Fundamental Phenomena

1. A plate or rod suitably prepared from a piezo-electric crystal, and provided with metallic coatings, can be brought into a state of vigorous longitudinal vibration when the coatings are connected to a source of alternating emf. of the right frequency. Under these conditions the plate reacts upon the electric circuit in a remarkable manner. Owing to the piezo-electric polarization produced by the vibrations, and to the absorption of energy in the plate, the apparent electrostatic capacity and resistance of the plate are not constant, but depend upon the frequency somewhat as does the motional impedance of a telephone receiver.[2] Over a certain very narrow range in frequency the capacity becomes negative. An analogy may also be drawn between the vibrating plate and a synchronous motor. The man-

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[1] Preliminary reports on this work have appeared in "The Physical Review," 17, page 531, 1921, and 18, page 142, 1921. The writer wishes to acknowledge the aid that he has received thru a grant from the American Association for the Advancement of Science.

[2] For an explanation of the motional impedance of a telephone receiver, see Proceedings of The Institute of Radio Engineers, volume 6, 1918, page 40.—Editor.

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ner in which the reactions upon the circuit are utilized will be described below. It is necessary, however, to consider the theory of the phenomenon first.

II. Piezo-Electric Theory

2. Four decades have elapsed since the discovery of piezo-electricity by the Curie brothers, and the prediction of the converse effect by Lippmann, which the Curies promptly verified. During this time much has been accomplished, both theoretically and experimentally, in systematizing and extending our knowledge of the behavior of crystals under static mechanical or electric stress. Only in very recent years, however, has consideration been given to rapidly varying stresses in piezo-electric crystals.

Nicolson[3] has had marked success in the use of suitably treated Rochelle salt crystals at telephonic frequencies, both as transmitters (direct piezo-electric effect) and as receivers (converse effect). The writer has also experimented with crystals at audio frequencies, but has devoted his attention chiefly to radio frequency vibrations in the neighborhood of the natural frequency of the crystal plates or rods.

We now summarize briefly those features of Voigt's theory of which we shall make use hereafter.[4]

When a piezo-electric crystal is mechanically strained, there results a dielectric polarization, the magnitude of which is proportional to the strain, and the direction and magnitude of which depend upon the direction of the strain and upon the class to which the crystal belongs. Except in the case of the class of crystals of lowest symmetry (triclinic), not all of the six components of strain are effective in producing a polarization. The higher the degree of symmetry, the smaller does this number become. Of the 32 classes, ten are devoid of piezo-electric properties.

The only two crystals the piezo-electric applications of which have hitherto been considered important are quartz and Rochelle salt; the latter, because it is far more strongly piezo-electric than any other crystal thus far examined; and quartz, because of its excellent mechanical qualities, which make it for most purposes decidedly preferable to Rochelle salt, in spite of its

[3]Nicolson, "Proceedings of the American Institute of Electrical Engineers," 38, page 1315, 1919; "Electrical World," June 12, page 1358, 1920.

[4]For a more complete statement, see Voigt, "Lehrbuch der Kristallphysik," Leipzig, 1910; Graetz, "Handbuch der Elektricität und des Magnetismus," Leipzig, 1914, volume 1, page 342; or Winkelmann, "Handbuch der Physik," 1905, volume 4, part 1, page 774.

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being only moderately piezo-electric. The present paper has to do only with quartz, tho obviously the theory applies to any piezo-electric crystal.

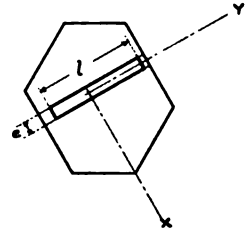

FIGURE 1—Section of a Quartz Crystal perpendicular to the Optical Axis

3. PIEZO-ELECTRIC PROPERTIES OF QUARTZ—Quartz belongs to the trigonal trapezohedral class of crystals. Figure 1 shows a cross-section of a quartz crystal, of which the Z-axis (optical axis) is perpendicular to the paper. The Y-axis is normal to two opposite prismatic faces. Owing to the threefold symmetry of quartz, the Y-axis may be drawn in any one of three directions 120° apart. The three X-axes (electric axes) are perpendicular to the Z- and Y-axes. For piezo-electric experiments, a plate is usually cut from the crystal with its length l, breadth b, and thickness e parallel respectively to the Y-, Z-, and X-axes. The two faces perpendicular to the X-axis are provided with conductive coatings, which may or may not be in actual contact with the quartz.

DIRECT EFFECT—If the plate is compressed in a direction parallel to the X-axis (*longitudinal effect*), the resulting polarization induces equal and opposite charges on the coatings, and the charges change sign with the pressure. Similarly, in the *transverse effect*, an endwise compression of the plate, parallel to the Y-axis, causes the coatings to become charged. A *compresions* of the plate parallel with the X-axis causes a polarization in the same direction as an *extension* parallel with the Y-axis.

CONVERSE EFFECT—In terms of the *converse effect*, if the plate is polarized by an external electric field in the same direction in which it would become polarized by compression along the X-axis, it tends to contract along the X-axis and to expand along the Y-axis.

From what has been said, two important conclusions should

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be borne in mind: first, that, in quartz, just as the *direct* effect may be produced by compression along either one of two directions (longitudinal and transverse effects), so both of these effects manifest themselves in connection with the *converse* effect; and second, that in both the direct and converse effects, a given strain is always associated with an electric polarization *in the same direction* and *of the same algebraic sign.*

Symbols

$l, b, e,$ length, breadth, and thickness of quartz plate or rod.

$\varepsilon, \partial,$ piezo-electric constant and modulus respectively. From section 11 on, a special meaning is attached to ∂.

$M, N, g,$ equivalent mass, resistance, and stiffness of resonator.

$x,$ displacement of end of resonator.

$F,$ equivalent mechanical force on resonator.

$E,$ voltage impressed on circuit.

$V,$ potential difference across resonator.

$D,$ piezo-electric polarization in resonator.

$I, i,$ currents in coil and resonator branches, Figure 3.

$C_1,$ normal capacity of resonator, vibrations damped.

$C_2,$ capacity of tuning condenser.

$C_1', C_1'',$ equivalent series and parallel capacity of resonator.

$R_1', R_1'',$ equivalent series and parallel resistance of resonator.

$C_a,$ "apparent" capacity of resonator.

$C_t, R_t,$ equivalent series capacity and resistance of entire circuit, Figure 3.

$R_{12},$ equivalent series resistance of resonator and C_2, together.

When printed without subscripts, x, F, E, V, D, I, and i denote instantaneous values. x_o and so on, denote maximum values.

$f,$ frequency.

$\omega,$ angular velocity $= 2\pi f$. ω_o and f_o denote resonance values.

4. In the case of quartz, the general polarization-strain equations reduce to the following form:

$$P_1 = \varepsilon_{11} x_x + \varepsilon_{12} y_y + \varepsilon_{14} y_z \qquad (1)$$

$$P_2 = \varepsilon_{25} z_x + \varepsilon_{26} x_y. \qquad (2)$$

P_1 and P_2 are X and Y components, respectively, of polarization (electric moment per unit volume), and the ε's are the *piezo-electric constants.* x_x and x_y are, in Voigt's notation, the components of extension (elongation or contraction per unit length), and y_z and so on, the components of shearing strain.

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If, instead of the components of strain, we have given the components of *stress*, (1) and (2) become

$$-P_1 = \partial_{11} X_x + \partial_{12} Y_y + \partial_{14} Y_z \quad (3)$$

$$-P_2 = \partial_{25} Z_x + \partial_{26} X_y. \quad (4)$$

The ∂'s are the *piezo-electric moduli*, which are related to the piezo-electric constants ϵ by equations involving also the elastic constants.

As is evident from equations (2) and (4), the polarization P_2 is produced only by shears, which may be neglected in the present paper, as may also the third term in (1) and (3). Of the two remaining terms on the right-hand side of (1) and (3) the first expresses the longitudinal effect, the second the transverse effect.

We shall need also the following expressions for the *converse effect*, in which the stresses along the X- and Y-axis are given in terms of the X-component E_1 of impressed electric intensity:

$$-X_x = \epsilon_{11} E_1 \quad (5)$$

$$-Y_y = \epsilon_{12} E_1. \quad (5a)$$

The other stress-components are of no concern here. The equation (5) expresses the longitudinal effect, and (5a) the transverse. In the applications described in the present paper, only the *transverse effect* is utilized.

One more fundamental equation must be added, namely the strain-equation for the transverse converse effect, which is analogous to (5a):

$$y = \partial_{12} E_1 \quad (6)$$

According to Voigt's theory, in the case of the class of crystals to which quartz belongs, $\epsilon_{26} = \epsilon_{12} = -\epsilon_{11}$, $\epsilon_{25} = -\epsilon_{14}$, $\partial_{12} = -\partial_{11}$, $\partial_{25} = -\partial_{14}$, and $\partial_{26} = -2\partial_{11}$. Hence in all only two different numerical values of ∂ and ϵ have to be known, and of these only one occurs in the present investigation. The following values of ϵ_{11} and ∂_{11} were determined by Riecke and Voigt:[5]

$$\epsilon_{11} = -4.77 \times 10^4, \quad \partial_{11} = -6.45 \times 10^{-8}.$$

The ϵ's and ∂'s as indeed all electric and magnetic quantities in this paper, unless otherwise stated, are in c. g. s. electrostatic units. As is evident from (1) and (2), ϵ has the dimensions of an electrostatic polarization, while from (3) and (4) it may be seen that ∂ has the dimensions of the reciprocal of an electric intensity. Hence

$$\epsilon = [k^{\frac{1}{2}} M^{\frac{1}{2}} L^{-\frac{1}{2}} T^{-1}], \quad \partial = [k^{\frac{1}{2}} M^{-\frac{1}{2}} L^{\frac{1}{2}} T].$$

Other observers have obtained slightly different values for

[5] Voigt, previous citation, pages 869-870.

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ϵ_{11} and δ_{11}. Fortunately, in the practical applications under consideration, the absolute values need not be accurately known.

III. Theory of Longitudinal Vibrations in Rods

5. The theory of electric reactions of vibrating piezo-electric plates is a structure built upon two main piers. First, there is the fundamental piezo-electric theory which has just been set forth; and second, the theory of longitudinal mechanical vibrations in rods, which will now be briefly summarized. The "plates" which the writer uses are, as far as mechanical considerations permit, in the form of thin rods. The advantage of this procedure, in addition to economy of material, is that the fundamental vibration together with harmonics of considerable purity may be secured, free from the disturbing effects of other modes of vibration. The theroretical treatment is also greatly simplified.

In a paper which is to appear in "The Physical Review," the general theory of forced longitudinal vibrations in rods is developed. The characterizing feature is the insertion in the equations of a symbol representing the *viscosity* of the material composing the rod; for that property of the rod whereby it absorbs energy and damps its own vibrations is as important here as is the resistance in an oscillating electric circuit. It is possible to measure the actual value of the viscosity by a purely electrical method, at any desired frequency; this, as well as the effect upon the resultant viscosity of air friction and of restraints imposed by the method of mounting, need not concern us here. It is only necessary to remark that a successful piezo-electric resonator must be prepared and mounted as to reduce the damping to a minimum.

6. When an alternating emf. is applied to the metallic coatings of a rod of this sort, an alternating mechanical stress is set up in the rod in accordance with equation (5a), which is uniform throut the mass of the rod. In this statement we neglect the "edge effect" of the condenser formed by the quartz and its coatings. Considering the thinness of the quartz and its high dielectric constant—about 4.5—this procedure is justifiable as a first approximation. In the paper referred to above, it is shown that the vibrations are the same as if the rod had impressed upon its ends two alternating forces, numerically equal to the actual internal stress, of like amplitude but opposite phases, and it is on this basis that the theory of forced vibrations is developed.

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The general equation of motion is

$$\frac{\partial^2 \xi}{\partial t^2} = P\frac{\partial^2 \xi}{\partial u^2} + Q\frac{\partial^3 \xi}{\partial u^2 \partial t}. \qquad (7)$$

ξ is the displacement, at the time t, of that cross-section of the rod whose undisturbed co-ordinate is u. P is defined by the equation $P = G/\rho$, where G is Young's modulus and ρ the density; P is therefore the square of the wave-velocity in absence of damping.[6] For brevity, we call Q the "viscosity," and treat it as a constant of the material, implying thereby that it is independent of the frequency. Its possible dependence upon frequency can be tested experimentally. The dimensions of Q are $[L^2 T^{-1}]$.

7. In the paper referred to, equation (7) is solved, but its application to actual cases of forced vibration is somewhat cumbersome. It is, however, shown that, for the fundamental vibration in the neighborhood of resonance, the rod may be replaced by a *fictitious "equivalent mass" M possessing one degree of freedom.* The equation of motion then has the familiar form

$$M\frac{d^2 x}{dt^2} + N\frac{dx}{dt} + g x = F = F_o \cos \omega t. \qquad (8)$$

Here M is half the actual mass of the rod, or $M = \frac{1}{2}\rho b l e$. In place of Young's modulus G in (7) we use the "equivalent stiffness," $g = M\omega_o^2$, which is related to G by the equation $g = \pi^2 beG/2l$. This follows from the equation $\omega_o = 2\pi f_o$, and $\sqrt{G/\rho} = 2lf_o$, $2l$ being the fundamental wave-length.[7]

x is the mechanical displacement at time t of the end of the rod, so that the actual elongation (or contraction) of the entire rod at any instant is $2x$.

M and g correspond to L and $1/C$ in an electric circuit hav-

[6] In crystalline media, the elastic constants depend, of course, upon the direction with respect to the axis of the crystal. Slight differences are found between individual crystals. Moreover, in the case of our rods, the elastic modulus is modified by lateral effects, unless the rod is extremely narrow, and by any discrepancy between the axis of the rod and the true Y-axis of the crystal. The effective value of G with the rods employed by the writer ranges from 8×10^{11} to 10×10^{11}. The value for quartz as given by Voigt is 8.51×10^{11}.

[7] Strictly, ω_o is the angular velocity when the amplitude of the *velocity* of the equivalent mass M is a maximum under forced vibrations; it is also the free angular velocity in absence of damping. The maximum amplitude of equivalent *displacement* x (equation (10)) comes (under forced vibrations) at the angular velocity $\sqrt{\frac{g}{M} - \frac{N^2}{2M^2}}$, while the angular velocity of free damped vibrations is $\sqrt{\frac{g}{M} - \frac{N^2}{4M^2}}$. The distinction between these three values may under ordinary circumstances be ignored.

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ing concentrated, as contrasted with distributed, constants. N is the equivalent resistance, and bears to the viscosity Q the relation $N=\pi^2\rho\, b\, e\, Q/2\,l$. For the proof of this the paper on longitudinal vibrations must be consulted. F is the equivalent impressed force. If the actual stress acts thruout the entire length of the rod, it may be proven that F is twice the actual force at any cross-section, or $F=2beX$, where X is the instantaneous stress. The expression for X in terms of the piezo-electric constant is given below, section 11.

We now write the steady-state solution of equation (8), which is of prime importance for the graphical method described in section 12:

$$x=x_o \sin(\omega t-\theta), \tag{9}$$

in which the maximum displacement is

$$x_o=\frac{F_o}{\omega\sqrt{N^2+\left(\omega M-\frac{g}{\omega}\right)^2}}, \tag{10}$$

and

$$\tan\theta=\frac{\omega M-\frac{g}{\omega}}{N}=\frac{\pi(\omega-\omega_o)}{\omega_o\Delta} \tag{11}$$

approximately, since $g/\omega=\omega_o M$ very nearly, and the logarithmic decrement per period, Δ, is, as in the electrical analogy, $N/2fM$.

The *power expended in maintaining vibrations*, as in the case of the electrical analogy, is easily proved to be

$$p=\frac{1}{2}\cdot\frac{F_o^2}{N}\ (ergs\ per\ sec.) \tag{12}$$

The *maximum stress when in resonance* may easily become so great as to break the quartz rod. On the assumption that the distribution of stress is sinusoidal, being zero at the ends, and for the fundamental, a maximum at the center, we find that the maximum stress at the center is $\pi x_o G/l$, where x_o is half the maximum elongation of the rod of length l, and G is Young's modulus.

IV. The Resonance Circle

8. In applying the foregoing theory to investigations with piezo-electric resonators, it is advantageous to employ a graphical method, based on the properties of what may be called, for brevity, the resonance circle. In principle, this curve is similar to the "motional impedance" circle which has been used by

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Kennelly and his collaborators in their studies of the telephone receiver.[8]

The equation of the curve in question is obtained by eliminating $\omega M - g/\omega$ between equations (10) and (11):

$$x_o = \frac{F_o}{\omega N} \cos\theta. \tag{13}$$

If ω were constant, this would be the polar equation of a circle passing thru the origin. In reality, as θ varies from $-90°$ thru zero to $+90°$, ω varies from zero to infinity. Nevertheless, when N is very small, as is the case with quartz, not only is the "diameter" of the "circle" in Figure 2 large, but that portion of the curve corresponding to the neighborhood of resonance comprises nearly the entire curve. For all other values of ω, θ is nearly equal either to $-90°$ or to $+90°$, so that with quartz, to the precision attainable by ordinary graphical methods, the curve cannot be distinguished from a perfect circle. The distortion of the curve owing to varying ω in Figure 2 is very greatly exaggerated in order to illustrate the principle.

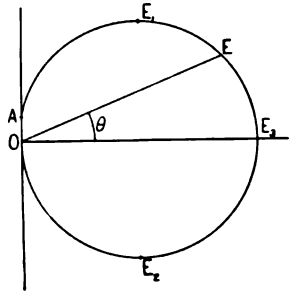

FIGURE 2—The Resonance Circle

$O\,E$ represents one value of the modulus x_o, with the corresponding argument θ. It has been found most convenient to draw the maximum modulus $O\,E_3$ horizontally to the right from the origin, and to lay off positive values of θ *below* the horizontal axis, so that *increasing frequency* is represented by a *clockwise movement* of the point E around the curve. Strictly speaking, the maximum modulus, $x_o = F_o/\omega N$, should be inclined slightly upwards, corresponding to a small negative value of θ. Here

[8] "Proc. Am. Acad. Arts and Sci.," 48, page 113, 1912; 51, page 421, 1915; "Proc. Am. Phil. Soc.," 54, page 96, 1915; 55, page 415, 1916. The circle diagram is also used by Hahnemann and Hecht, "Phys. Zeitschr.," 20, page 104, 1919, and 21, page 264, 1920, and by Wegel, "Journal of the American Institute of Electrical Engineers," 40, page 791, 1921.

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again the damping in the case of quartz is so slight that the maximum is practically the line $O E_3$.

$O A$ represents the "amplitude" when $\omega = 0$, that is, $O A$ is the equilibrium elongation under static stress at zero frequency, and must therefore have the value $X_0 l/2 G$. In the case of a typical quartz plate (Quartz Resonator N 2, to which further reference will be made), $3.07 \times 0.41 \times 0.14$ cm. ($1.21 \times 0.16 \times 0.055$ inch), the fundamental frequency of which is 89,870, the equilibrium elongation at either end under a potential difference of one electrostatic unit (300 volts) is 6.5×10^{-7} cm., while the maximum amplitude of vibration at either end is (by calculation) 0.0025 cm. (0.001 inch). Thus we see that $O E$ is about 4,000 times as large as $O A$: in other words, the growth of amplitude at resonance is 4,000-fold.

For our purposes, the advantage of the resonance circle as outlined above is two-fold: the moduli $O E$, being proportional to elongations of the plate, are thereby also proportional to the piezo-electric polarization; and since the argument θ is a phase angle, the resonance circle can be incorporated into an ordinary alternating current vector diagram in studying the reaction of the plate upon the circuit. We now come to a consideration of the latter.

V. Reaction of Piezo-Electric Resonator Upon Circuit

9. Description of Circuit—The circuit that I have most frequently used in these experiments is that shown in Figure 3.

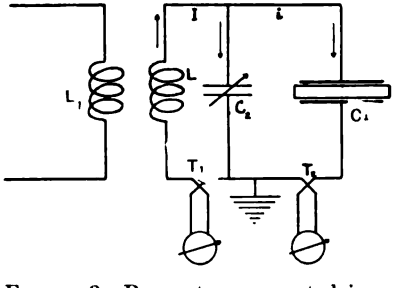

Figure 3—Resonator connected in a Secondary Circuit, with Thermo-elements for measuring Currents. The arrows indicate positive directions in the three branches

The main conclusions derived from the following paragraphs are, however, applicable to any circuit to which the resonator is likely to be connected. L_1 is a coil of about 5 millihenrys in

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the anode circuit of a vacuum-tube generating set kindly loaned by the Western Electric Company, so designed as to minimize the effect of load upon frequency. The latter is an extremely important requirement, and was found to be admirably fulfilled. Loosely coupled to L_1 is the litzendraht coil L of 3 or 4 millihenrys, in parallel with which are the precision variable condenser C_2 (maximum 1,500 $\mu\mu$f.) and the piezo-electric resonator C_1. Most of the quantitative work has been done with resonators about 3 cm. (1.2 inch) long, having frequencies around 90,000, corresponding to radio wave lengths of the order of 3,000 meters. References to other wave lengths will be made later, and also to the method of mounting C_1. T_1 and T_2 are thermo-elements of resistances 4.5 and 2,810 ohms, respectively, T_2 being a Western Electric vacuum thermo-element. The thermo-elements are in Figure 3 represented as connected to separate galvanometers, but in practice a single Leeds and Northrup high-sensitivity galvanometer of 10 ohms resistance was employed, provided with a change-over switch and suitable shunts. It was thus possible, at each frequency used, to measure the current I in the coil, and the current i flowing to the resonator. C_2 was provided with a worm gear for fine regulation, and readings were taken by means of a lamp and calibrated scale, a mirror being mounted on the condenser handle. By means of a specially constructed parallel-plate air condenser with micrometer control in the generating circuit an extremely fine regulation of frequency was possible. The voltage induced in L was practically constant over the small range in frequency involved.

10. The most instructive data are obtained by observing C_2, I, and i at a number of frequencies, and plotting the results as in Figure 6. These curves will be further discussed in section 15. At each frequency, C_2 is varied until either I or i is a maximum.

At a certain critical frequency, the absorption of energy by the resonator is so great that the coil-current I falls almost to zero, even when C_2 is at its most favorable setting, as represented in Figure 6. Any change in C_2 causes I to decrease still more: but a slight change in frequency causes I to increase enormously, showing that the mechanical tuning of the resonator is very much sharper than the electrical tuning of the circuit. At this point, then, *I is a maximum with respect to C_2, but a minimum with respect to f.*

Further consideration of Figure 6 will be deferred until the theory of the resonator's reactions has been given.

11. Theory of the Reactions—We assume that an emf.

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$E_o \cos \omega t$ is impressed upon coil L, Figure 3, E_o being constanl at all frequencies. Let V represent the instantaneous potentiat difference across C_2 and C_1, which, of course, varies with frequency, and R the combined resistance of L and T_1. The capacity of the coil should be included in C_2. The impedance of C_1 is so great that the resistance of T_2 may, as a first approximation, be neglected. We then have

$$E = E_o \cos \omega t = V + L\dot{I} + RI. \tag{14}$$

The link between this equation and that for the vibration of the resonator is the quantity V. For the electric field in the quartz has the value V/e, where e is the thickness of the quartz; and by equation (5b), the mechanical stress is $X = \varepsilon V/e$. From section 7, we see that the value of the equivalent force F in equation (8) must be $F = 2\,b\,e\,X = 2\,\varepsilon\,b\,V$. Equation (8) may, therefore, be written thus:

$$2\,\varepsilon\,b\,V = M\ddot{x} + N\dot{x} + Gx. \tag{15}$$

Next, we consider the components of polarization within the resonator. Let D_1 represent the component due to the potential difference between the coatings. If this p. d. is V, and if the air-gaps between coatings and crystal be neglected, then D_1 is the ordinary displacement in the dielectric, as given by the equation $D_1 = k\,V/4\,\pi\,e$. k, the dielectric constant of quartz, has the value 4.5, approximately.

A second component of electric polarization, that which is responsible for all the effects described in this paper, is caused by the deformation of the resonator. Using the same notation as heretofore, we assume that at any given instant the p. d. across the resonator is V, and that the total elongation (difference, + or −, between instantaneous length and normal length) is $2\,x$. Of this elongation, a portion, say $2\,x_1$ is that which would be produced under static conditions with a constant potential-difference V. This portion is the "equilibrium elongation," and exerts no reaction upon the circuit. The value of $2\,x_1$ may be derived from (6) thus:

$$y_y = \delta_{12}\,E_1 = \delta_{12}\,\frac{V}{e}.$$

Further, we have the fundamental relation $2\,x_1 = l\,y_y$, hence $2\,x_1 = \delta_{12} V\,l/e$. x_1 is readily seen to be the same as the $O\,A = X_o\,l/2\,G$ in section 8, since by Hooke's law $y_y = X_o/G$. That portion of the total elongation $2\,x$ which is due to the vibrations, and therefore, effective in producing an electric reaction, is $2\,x - 2\,x_1$. Applying equation (1) (only the second term on the

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right side of which remains, since x_x and y_z do not appear) to this elongation, we find $P_1 = 2\,\varepsilon_{12}\,(x - x_1)/l$, or, writing D in place of P_1, dropping the subscript from ε_{12}, replacing $2\,x_1$ by its value above, and letting δ represent the quantity $\delta_{12}\,l/e$,

$$D = \frac{\varepsilon}{l}(2\,x - \delta\,V). \tag{16}$$

At frequencies sufficiently removed from resonance, $2\,x$ may be so small as to be even less than δV; but with quartz, in the neighborhood of resonance, the static elongation δV is negligible, as stated already in section 8.

Equations (14), (15), and (16) contain four unknown quantities, namely: V, I, x, and D. The fourth equation necessary to a solution of the problem is found either in the expression for the resonator current:

$$i = b\,l\,(\dot{D}_1 + \dot{D}) = C_1\,\dot{V} + b\,l\,\dot{D}, \tag{17}$$

or preferably that for the coil current:

$$I = C_2\,\dot{V} + i = C_2\,\dot{V} + b\,l\,(\dot{D}_1 + \dot{D}) = (C_1 + C_2)\,\dot{V} + b\,l\,\dot{D}. \tag{18}$$

Equation (18) follows from Kirchhoff's first law.

These equations are simply expressions of the principles that current is time-rate of change of dielectric flux, and that the polarization in C_1 has the two components D_1 and D discussed above. Dielectric flux is of course polarization times area $b\,l$.

From equations (14), (15), (16), and (18) a single differential equation of the fourth order may be formed, giving x as a function of time in terms of impressed voltage E and the circuit constants. A much more convenient and satisfactory procedure, exhibiting at a glance all the characteristic phenomena, is the graphical method now to be described.

12. Graphical Method of Solution—We shall construct a vector diagram showing quantitatively not only the current and voltage components and their phases, but the effective capacity and resistance of the resonator at any frequency as well. Our starting-point is the resonance circle described in section 8. For the purpose of this paper it is amply accurate to regard the curve as a true circle, letting the distance $O\,A$, Figure 2, equal zero, and neglecting the second term in equation (16). Equation (16) then reduces to

$$D = \frac{2\,\varepsilon\,x}{l}, \tag{19}$$

or, in terms of maximum values,

$$D_o = \frac{2\,\varepsilon\,x_o}{l}. \tag{19a}$$

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D is thus approximately proportional to x; in other words, *the resonance circle is applicable also to the piezo-electric polarization D, and consequently to the piezo-electric flux in the resonator, D b l.*

The first problem before us is, to represent I graphically as the vector sum of the two terms in equation (18). This involves, in the first term, the phase-angle of V, which is not yet known. We therefore write V in the form

$$V = V_o \cos(\omega t - \gamma), \tag{20}$$

leaving γ to be determined later. The derivative is

$$\dot{V} = -\omega V_o \sin(\omega t - \gamma).$$

For the second term in (18), we have the following relations, from equations (9) and (19), together with (15) and (20):

$$b l \dot{D} = 2 b \varepsilon \dot{x} = 2 b \varepsilon \omega x_o \cos(\omega t - \gamma - \theta)$$
$$= 2 b \varepsilon \omega V_o x_o' \cos(\omega t - \gamma - \theta). \tag{21}$$

x_o' equals x_o/V_o, and is therefore the amplitude of vibration per unit maximum potential difference. Similarly, D' and I' will signify D/V_o and I/V_o, respectively. Hence equation (18) may be expressed thus:

$$\frac{I}{\omega V_o} = \frac{I'}{\omega} = -(C_1 + C_2) \sin(\omega t - \gamma)$$
$$+ 2 b \varepsilon x_o' \cos(\omega t - \gamma - \theta). \tag{22}$$

In Figure 4, the two terms on the right-hand side of equation (22) are represented by the vectors $O\,q$ and $O\,E$, respectively. $O\,X$ is the positive direction corresponding to $\sin(\omega t - \gamma)$, and $O\,Y$ that corresponding to $\cos(\omega t - \gamma)$. The moduli $O\,q$ and $O\,E$ are assumed equal to $-(C_1 + C_2)$ and $D_o' b l = 2 b \varepsilon x_o'$, respectively.[9] As ω varies, $O\,q$ remains constant (unless C_2 is altered), while the point E describes the resonance circle. The half of the circle to the left of $O\,Y$ in Figure 4 is the low-frequency side, for which θ is negative. $O\,A$ is thus the vector representing I'/ω, and the modulus OA is equal to the maximum value I_o'/ω.

Our graphical construction so far has been based upon equations (15), (16), and (18). We will now make use of (14) in order to make the transition from I' to I. Since this involves only multiplying I' by ωV_o, the argument $\theta_2 = \angle XOA$ remains unchanged. We have

$$I' = I_o' \sin(\omega t - \gamma + \theta_2), \tag{23}$$

[9] If the material and construction of the resonator are such as to make the retention of the second term $\partial \dot{V}$ in equation (16) desirable, it is only necessary to shift the center of the circle in Figure 4 to the left by an amount equal to $\partial\, b\, l$, leaving all else unchanged. In the problem of the telephone receiver, the analogue of the term $\partial \dot{V}$ is Kennelly and Affel's "damped impedance" ("Proc. Am. Acad. Arts & Sci.," 51, page 423, 1915).

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and find, by substitution of (20) and (23) in (14), and division by $\omega^2 L V_o$,

$$\frac{E}{\omega^2 L V_o} = \frac{E_o}{\omega^2 L V_o} \cos \omega t = \frac{1}{\omega^2 L} \cos(\omega t - \gamma) + \frac{I_o'}{\omega} \cos(\omega t - \gamma + \theta_2) + \frac{R I_o'}{\omega^2 L} \sin(\omega t - \gamma + \theta_2). \quad (24)$$

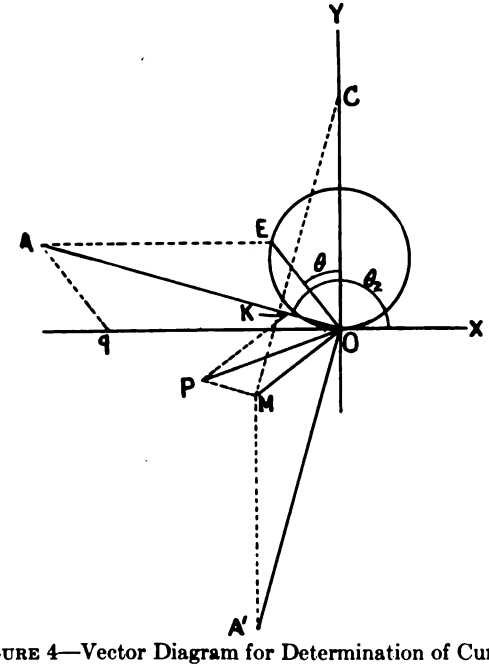

FIGURE 4—Vector Diagram for Determination of Current I

The advantage of this form is, that the second term on the right-hand side is, as we have seen, already represented by the vector OA in Figure 4. If now we lay off $OC = 1/\omega^2 L$ along OY, $OA' = OA$, $\angle AOA' = 90°$, and $OK = R \cdot OA/\omega L$, we see that the three terms on the right of equation (24) are correctly represented by the three vectors OC, OA', and OK, respectively. The resultant of OC and OA' is OM, and the final resultant is OP. By (24), the modulus OP is therefore equal to $E_o/\omega^2 L V_o$, and $\gamma = \angle POC$. These operations might of course be performed analytically, but the graphical method is rapid, and amply accurate.

If the frequency is too low for the resonator to vibrate perceptibly, OE is practically zero, $Oq > OC$ (that is, $C_1 + C_2 > 1/\omega^2 L$), and, if R is small, OP is directed nearly vertically down-

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ward and OA to the left, indicating the usual lead of nearly 90° if the circuit is tuned electrically to approximately the frequency of the resonator. At frequency f_o (natural resonator frequency), the angle POA (phase angle between E and I) may be positive, zero, or negative, depending upon the value assigned to the known capacity C_2.

The actual value of I is not shown directly on the diagram. It may, however, be found as follows. We have, from statements made above,

$$V_o = \frac{E_o}{\omega^2 L} \cdot \frac{1}{OP}, \tag{25}$$

and

$$I_o = I_o' V_o = \frac{E_o}{\omega L} \cdot \frac{OA}{OP}. \tag{26}$$

13. The construction of the vector diagram may be simplified, and its range of application extended, by the following modification, shown in Figure 5. First we draw the resonance circle to the same scale as in Figure 4, namely with modulus $OE = 2b\,\varepsilon\,x_o'$, but with the angle θ laid off, as in Figure 2, from OX instead of from OY. $Oq = C_1 + C_2$, where C_2 may have any value. Draw EA and qA parallel to Oq and OE, respectively; also PCT perpendicular to OA, letting $PC = R : OA/\omega L$. Draw AP, cutting OC at V. By comparison with Figure 4 we see at once that the phases of X, V, E, and I are given by the directions of OE, OY, AP, and TP, respectively, and that

$$\theta_2 = \angle AOY' \tag{27}$$

$$\gamma = \angle AVO \tag{28}$$

$$V_o = \frac{E_o}{\omega^2 L} \cdot \frac{1}{AP} \tag{29}$$

$$I_o = \frac{E_o}{\omega L} \cdot \frac{OA}{AP}. \tag{30}$$

The entire diagram is determined by the electric constants and the characteristic resonance circle of the resonator. From the above equations, V_o and I_o and their corresponding phases may therefore be found for any frequency, in terms of the impressed E_o. A comparison of these theoretical values with those derived from observation can then be made, as will be seen in section 15. For the present it need only be remarked that, as the point E travels around the circle clockwise (increasing frequency), V_o and I_o pass thru a minimum, which is more pronounced the smaller the value of R, that is, the shorter the line

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$P\,C$. The range in ω is usually so small that the distance $O\,C$ may be given a mean value, practically independent of frequency.

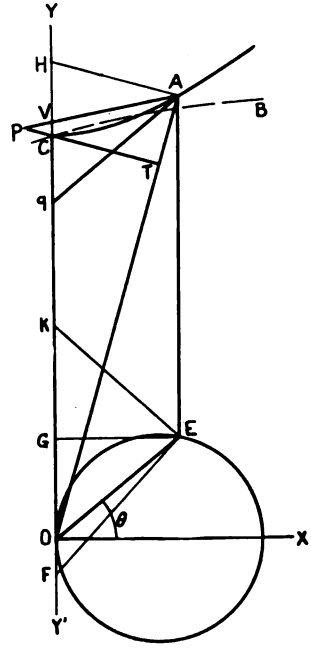

FIGURE 5

Vector diagram showing reactions of resonator upon electric circuit. Summary of relations derived from this diagram:

$$OE = D_o' b l \qquad I_o = \frac{E_o}{\omega L} \cdot \frac{OA}{PA} \qquad C_1' = FK \qquad R_1' = \frac{1}{\omega} \cdot \frac{EG}{FE^2}$$

$$OC = \frac{1}{\omega^2 L} \qquad i_o = \frac{E_o}{\omega L} \cdot \frac{FE}{PA} \qquad C_1'' = FG \qquad R_1'' = \frac{1}{\omega \cdot EG}$$

$$Oq = C_1 + C_2 \qquad Z_1 = \frac{1}{\omega \cdot EF} \qquad C_1' = OH \qquad R_{12} = \frac{1}{\omega \cdot OC} \cdot \frac{CT}{OA}$$

$$V_o = \frac{E_o}{\omega^2 L} \cdot \frac{1}{AP} \qquad C_1'' = OF \qquad C_a = H_q + OF \qquad R_t = \frac{1}{\omega \cdot OC} \cdot \frac{PT}{OA}$$

14. We will next consider the graphical solution for the case of greatest practical importance, namely that in which C_2 at each frequency is adjusted to such a value as to make the current I a maximum. We will call this the *condition of I-resonance.* In an ordinary resonance circuit this would mean simply bringing I into phase with E. But when the piezo-electric resonator is present, we must proceed as follows. From equation (30), since over the range considered ω is nearly constant, it is evident that I_o will be a maximum when C_2 is so adjusted as to make the ratio

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$O\,A/A\,P$ a maximum. That is, since $O\,q = C_1 + C_2$, that location of q on the line $O\,Y$ must be found for which $O\,A/A\,P$ is a maximum, subject to the condition that, for any given frequcncy, E is fixed and $A\,E$ must remain parallel to $O\,V$. The point C is fixed, since $O\,C = 1/\omega^2 L$, and $P\,T$ remains always perpendicular to $O\,A$. It is easily proven that *A must lie on one branch of a rectangular hyperbola, as shown in Figure* 5, *the center of which is midway between C and O.* The hyperbola, which will usually be rather flat, is readily drawn when two or three of its points have been determined by simple geometrical construction. Therefore, when the circuit is at every frequency tuned to resonance by maximum I, the construction consists simply in drawing a line from E parallel to $O\,V$, meeting the hyperbola at A; and then drawing Aq parallel to $E\,O$. Thus we find, *not only the resonant current, but the corresponding capacity $C_2 = O\,q - C_1$, as well.*

15. We will next examine the graphical construction for the *resonator-current i*, and from it find the effective capacity and resistance of the resonator. The starting-point is equation (17), and the method exactly similar to that by which the vector representation of I_o (see equation (30)) was derived from equation (18). We therefore pass at once to the result:

$$i_o = \frac{E_o}{\omega L} \cdot \frac{F\,E}{P\,A}. \qquad (31)$$

This differs from equation (30) only in that in place of $O\,A$ we have $F\,E$, the resultant of $O\,F$ and $O\,E$. The point F is taken such that $O\,F = C_1$, while, as has been shown above, $O\,E = D_c'\,bl$. The vectors $O\,F$ and $O\,E$ correspond to the two terms on the right side of equation (17). In the case of a good resonator, $O\,F$ is small in comparison with the diameter of the circle.

The resonator current i leads the potential difference V by the angle $F\,E\,G$; G being the foot of the perpendicular from E upon $O\,V$. This angle, when out of resonance, becomes 90° corresponding to the fact that the resonator is then a simple condenser, and absorbs no energy. The *maximum* of i would, if V were constant, come practically at that frequency for which FE is a maximum. But, as has been seen, V varies in a manner determined in part by the arbitrary variation of the condenser C_2. Hence the variation of i with frequency depends upon C_2, that is, upon the distance Oq. If C_2 is varied in such a manner as to keep I a maximum at each frequency ("*I-resonance*," section 14), then A, the operating point for the current I, lies on the

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hyperbola $C\,A$, and the value of $P\,A$ to substitute in (31) in determining i_o is that shown in Figure 5.

In Figure 6 are shown the results of a series of observations made with quartz resonator N 2, already mentioned in section 8.[10] The arrangement shown in Figure 5 was used, the circuit being adjusted for the condition of I-resonance at each frequency by means of C_2. Values of C_2, I, and i are plotted as functions of

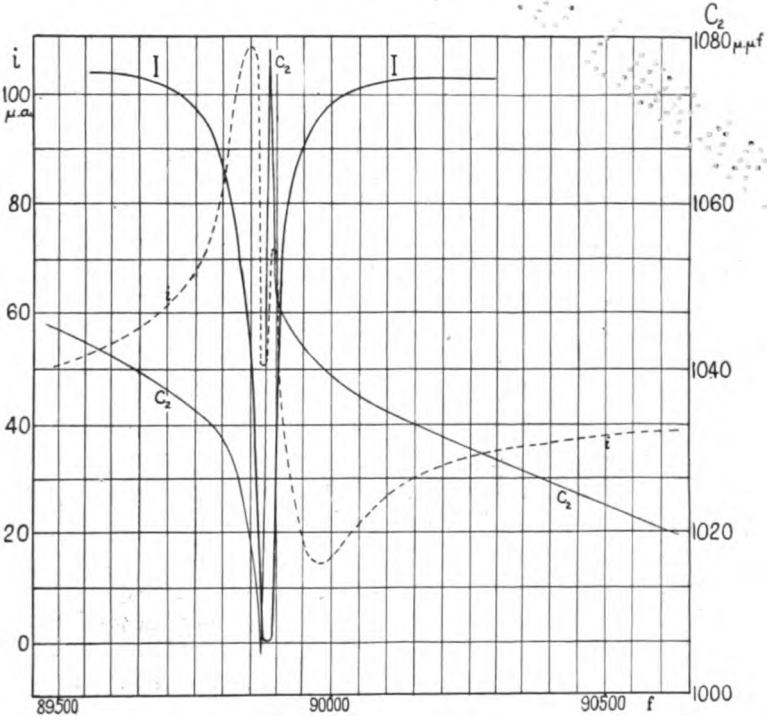

FIGURE 6—Characteristic curves of piezo-electric Resonator N2. The values of current I in micro-amperes are obtained by multiplying by fifty the ordinates of the I-curve, expressed in terms of the i-scale

frequency. The minimum and maximum of C_2 correspond to the lowest and highest positions of the point q in Figure 5. The minimum of I comes at a frequency between the frequencies for maximum and minimum C_2, as it should according to theory (see equation (30). Attention is directed especially to the sharp ness of resonance, and to the practical extinction of the current I at resonance. This suggests a possible application of the resonator as a wave-filter.

[10] These observations, which required no little patience and skill, were made by Mr. T. Fujimoto.

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The form of the i-curve is more complicated, since the resonator current, as is seen by inspection of equation (31), depends essentially upon both $F E$ and $P A$. As the point E travels around the resonance circle, the variations in $F E$ and $P A$ are such that i passes thru two maxima and two minima. The i-curve in Figure 6, which is based on direct observation, is in full agreement with the theory.

The values of C_2 shown in Figure 6 are for the variable condenser alone, uncorrected for the capacity of the coil, which was about 20 $\mu\mu$f.

By constructing the resonance circle as indicated in section 19, the equivalent parallel capacity of the resonator may be found according to equation (36). For resonator N2 the maximum value is 41.5, minimum -32.5 $\mu\mu$f. The normal value is 4.5 $\mu\mu$f. The logarithmic decrement is 0.00066.

Figure 5 is essentially a diagram of admittances, each vector having the dimensions of a *capacity*. In this sense the resonance circle represents what may be termed the *motional admittance* of the resonator.

One interesting deduction from Figure 5 is that when C_2 is adjusted for I-resonance or for i-resonance, as long as the resonator is vibrating, the current I *lags behind* E by the angle $A\ P\ T$ (see section 12). In other words, the resonator load is not capacitive, but *inductive*. This is also made evident by the large value of the total equivalent capacity C_t (equation (38)) of the circuit, since by Figure 5, $O\ H$ is always larger than $O\ C$, which latter represents $1/\omega^2\ L$.

If one were to take the difference between the value of C_2 with resonator vibrating and that with the vibrations damped, setting for I-resonance in each case, this difference would not be a measure of the capacity of the resonator, since the phase of the current would be different in the two cases. The difference between the two C_2 values would be Cq in Figure 5; it passes thru positive and negative values in a manner similar to C_a and C_1'' (sections 17 and 18).

16. The Condition of i-Resonance—In section 10 it was stated that C_2 might be varied in such a way as to keep the *resonator-current* i a maximum at each frequency. Altho the settings of C_2 in this case differ only slightly from those required for I-resonance, the distinction must not be overlooked. It will be remembered that the hyberbolic locus $C\ A$ of the operating point A was derived from the condition that $O\ A/A\ P$ in equation (30) should be a maximum. In the present case, for i-reson-

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ance, we must find a locus for A such that $F\,E/P\,A$ in (31) shall be a maximum (ω may be regarded as practically constant over the narrow range involved). Since $F\,E$ depends only on ω, it follows that i_o is a maximum when $P\,A$ is a minimum, that is, when $P\,A$ is perpendicular to $A\,E$. It is not difficult to prove that under these conditions the locus of A is not a hyberbola, but a *parabola*, with its axis horizontal and midway between O and C, and its vertex to the left of $O\,C$ by a distance equal to $O\,C^2/4\,P\,T$. The dotted line $C\,B$ in Figure 5 represents that portion of the parabola which comes into play here. Its closeness to the hyperbola $C\,A$ shows how nearly identical the two types of resonance are, especially when $O\,C$ is relatively large (L small, C_2 large). When the parabolic arc $C\,B$ has been drawn, the value of i_o is easily computed for any frequency.

By using a variometer for L, it would of course be possible to leave C_2 fixed and tune for electrical resonance by varying L. This would lead to a different graphical construction, offering no special advantage.

17. Equivalent Resistance and Capacity of Resonator—These are found by forming the expressions for impedance and admittance, which are then resolved into their R and X components. Since we are dealing with ratios, it is unnecessary to transform maximum into effective values of current and voltage.

Considering first the resonator alone, we have, for any frequency $\omega/2\pi$, the maximum current given by equation (31), and maximum potential difference by (29). Hence the impedance Z_1 of the resonator is evidently

$$Z_1 = \frac{V_o}{i_o} = \frac{1}{\omega \cdot FE}. \tag{32}$$

The angular relations are those of the triangle $F\,E\,G$, Figure 5. Hence we have (still using electrostatic units) for the *equivalent series resistance* R' *and capacity* C' *of the resonator*

$$R_1' = \frac{1}{\omega} \cdot \frac{EG}{FE^2} \tag{33}$$

$$C_1' = \frac{EF^2}{FG} = FK, \tag{34}$$

the line $E\,K$ being drawn perpendicular to $E\,F$. C_1' becomes infinitely great at resonance.

For some purposes the *equivalent parallel resistance* R_1'', *and capacity* C_1'', are more useful. They are found by taking the reciprocal of Z_1 (admittance), still using the triangle $F\,E\,G$. By writing the expressions for conductance and susceptance we have

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$$R_1'' = \frac{1}{\omega \cdot EG} \tag{35}$$

$$C_1'' = FG. \tag{36}$$

The last equation is noteworthy, as it makes the variation of equivalent parallel capacity with frequency evident from a glance at Figure 5. These four expressions for resistance and capacity depend only on the resonator, and not at all upon the rest of the circuit.

18. Effect of Resonator Upon Constants of Circuit—We seek expressions, in terms of vectors in Figure 5, for the following quantities: equivalent series resistance R_t and capacity C_t of entire circuit; equivalent series resistance R_{12} of the resonator and C_2 together; and the *apparent* capacity C_a of the resonator, this being defined as the difference between C_t and C_2.

The method is similar to that followed in section 17. From equation (30) we find the impedance of the entire circuit to be $Z_t = E_o/I_o = \omega L \cdot AP/OA = A\,P/\omega . O\,C . OA$, since $OC = 1/\omega^2 L$. From the statement in section 13 respecting phase angles it is evident that our impedance triangle is similar to the triangle $A\ T\ P$ in Figure 5. By resolving Z_t into components we readily find that

$$R_t = \omega L \cdot \frac{PT}{OA} \tag{37}$$

$$C_t = \frac{OC \cdot OA}{OT} = OH. \tag{38}$$

H is the intersection of $O\,C$ with a perpendicular erected on OA at A. Now remembering that $O\,q = C_1 + C_2$, and $C_1 = O\,F$, we see at once that the *apparent capacity* C_a of the resonator is

$$C_a = C_t - C_2 = O\,H - O\,q + O\,F = H\,q + O\,F \tag{39}$$

The apparent capacity of the resonator thus differs from both the equivalent series and the equivalent parallel capacity of the resonator alone, being a function also of C_2. The excess of C_a over C_1'' is greater the smaller the value of C_2.

The equivalent series resistance R_{12} of C_2 and the resonator is of importance, because it represents the increase in effective resistance of the circuit brought about by the absorption of energy in the resonator. It may be computed by the familiar method from C_2, C_1'' and R_1'', but more simply by writing $R_{12} = R_t - R$. Using the graphical representation of R given in section 13 we find

$$R_{12} = \frac{1}{\omega . OC} \cdot \frac{CT}{OA}. \tag{40}$$

Since $O\,A$ does not vary greatly over the range of resonance,

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R_{12} is evidently greatest when $C\ T$ is greatest, that is, when $O\ E$ in Figure 5 is a maximum (mechanical resonance). By substituting the appropriate values in (40), the value of R_{12} may be computed and compared with that derived from observation.

All the results in sections 17 and 18 are entirely independent of the question of electrical resonance, and hold for all values of C_2 and L.

Thus we see that the performance of the resonator is completely described in terms of the resonance circle and the accompanying vectors in Figure 5.

19. Applications of Graphical Method—Besides the purpose that it serves in connection with the experimental test of the theory, the graphical method is useful in predicting the performance of the resonator in any circuit to which it may be connected, and also in finding the coefficient of viscosity Q of the material of the resonator.

In testing the theory, it must be stated at the outset that, owing to our ignorance of the actual amplitude of vibration x_o of the ends of the resonator, and owing also to the fact that we are not certain of the precise value of the piezo-electric constant ε, especially at radio frequencies, the diameter of the resonance circle must be found indirectly from the electrical data. A check on this could be obtained if x_o could be measured, and on the other hand observation of x_o could be employed for finding ε at high frequency. I hope soon to undertake the measurement of x_o with the aid of an interferometer. There are several possible ways of determining the resonance circle, based on observations of I, i, and C_2, in some cases inserting also a known resistance in series with L. Only one such method need be described here.

In this method we adjust C_2 to satisfy the condition of I-resonance at each frequency. Let it be recalled that the point A in Figure 5 then lies on the hyperbola $C\ A$; that $q\ A$ is equal and parallel to $O\ E$; and that $O\ q = C_1 + C_2$. As the impressed frequency passes thru resonance, E travels around the circle, and $O\ q$ passes thru a minimum, followed by a maximum. The points on the resonance circle corresponding to these two values of $O\ q$ are those points where the hyperbola $C\ A$, if moved vertically downward parallel to itself, would be tangent to the circle. Conversely, if the two values of $O\ q$ are known from observations of C_2, the circle fulfilling the above requirements is easily determined.

The same method may also be applied by adjusting C_2 at each frequency so as to satisfy the condition of i-resonance.

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Exactly the same procedure is followed, save that the parabola $C\,B$, Figure 5, is used in place of the hyperbola $C\,A$. This has its advantages, inasmuch as, when R is made as small as possible, the parabola becomes practically a horizontal straight line. The points on the circle corresponding to the maximum and minimum values of C_2 are then the "quadrantal points" E_1 and E_2, Figure 2, for which $tan\ \theta = \pm 1$.

By observing the frequency corresponding to any point on the circle for which θ is known, for example the point of tangency with a hyperbola mentioned above, or one of the quadrantal points, we may find the decrement Δ in equation (11). Having found Δ, the value of ω for any θ is easily computed. The theoretical value of C_2, i, or I for any frequency may then be found by construction.[11]

VI. Construction of Resonators

20. It was found in the early stages that strongest and most constant results were obtained when the crystal plate was placed between and not quite touching the metallic coatings. For the latter small flat plates of brass are now used, of the same size as the crystal or somewhat shorter.[12] Light contact between quartz and brass at one or two points is, for most purposes, of no consequence. The quartz rod may be supported by a thread tied about its center, or balanced on edge upon a small block. Successful tests have also been made with a quartz rod or plate silvered on both sides. It is easy to deposit chemically a coating of silver sufficiently thick for the electrical effects, without decreasing the frequency more than one or two tenths of a per cent. The advantages of this method are not sufficient, however, to offset the difficulty of making an electrical contact with the silver that is both permanent and delicate.

For a portable unit, the best method of mounting is to let the crystal plate lie in a small pocket in which it is just free to vibrate. The sides of the pocket are formed by the brass "coatings," the

[11] In the paper on longitudinal vibrations already mentioned, it is proved that $\Delta = \pi\,\omega\,Q/c^2$, where c, the wave velocity, equals $4\,l^2 f^2$ for the fundamental vibration. Thus by finding Δ we can compute the coefficient of viscosity Q. It is planned to deal with this more fully in a later paper. Due regard must of course be paid to air-friction.

[12] When the metallic coatings are shorter than the crystal, the behavior of the resonator is qualitatively unchanged. The consequent small modifications to the theory are easily made, if needed. Strictly, a correction should also be made in the theory on account of the air-space between crystal and the coatings. This is not so simple a matter. Fortunately the essential performance of the crystal is not altered, except in intensity, by the air space, and for quantitative tests of the theory, it is possible so to mount the rod as to make the air-space negligible.

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bottom is of glass, and the ends of bakelite or hard rubber. By its own vibrations the plate keeps itself sufficiently free from contact with sides and ends, while any particles of dust on which it may rest serve as roller bearings to reduce friction with the bottom of the pocket.

Figure 7 shows a partially completed unit containing four plates, of which the longest is about 3 cm. (1.2 inch) in length. To the left is seen a small resonator containing one 3 cm. plate.

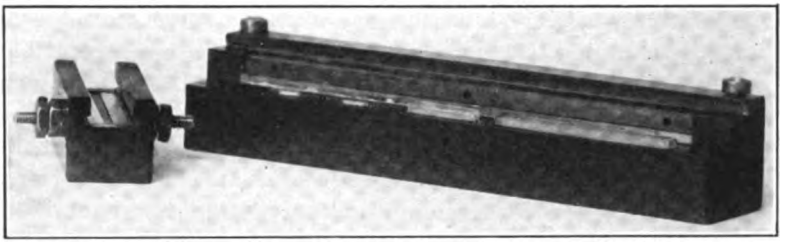

FIGURE 7—Quartz Resonators. Left: a single unit, mounted, for 3,040 m. Right: partially completed mounting for four quartz plates, which are seen lying on the front edge of the bakelite base. The wave-lengths are approximately 3,000, 1,200, 500, and 400 meters. These plates will stand on edge on the glass strip immediately behind them, having as one common "coating" the long brass bar which rests on the glass. The four individual "coatings," and the spacers to keep the quartz plates in place, are not shown.

21. THE CONSTANTS OF QUARTZ are such that the radio wave length in meters is roughly 100 times the length of the resonator in millimeters (2,500 times the length in inches). Concerning the relative dimensions of the crystal plates, the following are determining factors, which follow directly from the theory. Since all the essential phenomena are proportional to the diameter of the resonance circle as drawn in Figure 5, and since this diameter (compare section 13) contains the width b of the plate as a factor, it follows that b should be large. The limit to the width of the plate is set by the fact that disturbing modes of vibration enter in when the plate is not relatively narrow. In practice, the best value of the ratio l/b has been found to vary from 2 for the smallest plates (length about 2 mm. or 0.08 inch) to 10 or 20 for the largest. Thin plates are always an advantage, since for same voltage the electric field in the quartz is then more intense.

If the air-space is increased, or if the ends of the quartz extend far out beyond the brass coatings, the frequency is slightly raised. In order to understand this, one should compare the polarized plate with a short, wide bar magnet. When the coatings are close to the quartz, they and the associated circuit are

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analogous to a massive yoke of highly permeable material, allowing the induction to attain the greatest possible value. As the air gap increases, the plate partially depolarizes itself, owing to the turning back of some of the lines of electrostatic induction that are produced by its state of strain. The piezo-electric action of this depolarizing component is always to tend to make the plate regain its normal form; that is, the effective value of Young's modulus is larger, the greater the air gaps. In the most extreme case hitherto observed, the increase in frequency when the coatings, originally touching the quartz, were entirely removed, amounted to about 0.6 per cent. Hence no perceptible inaccuracy need be feared from this direction. Data at present available indicate that the frequency of the larger quartz resonators, when permanently mounted, is constant at least to within one part in 10,000. The quartz-steel resonators are subject to a small correction for temperature, amounting to about 0.01 percent decrease per degree centigrade.

The decrement of the resonator is easily proven to be independent of its cross-section, but directly proportional to the frequency. Resonators for large wave lengths are therefore more efficient and more sharply tuned than those for short waves. This statement assumes that the viscosity Q is constant. The larger resonators are for this reason much more in danger of fracture from excessive voltage. It is doubtful whether a good resonator for 3,000 meters will stand safely as much as 50 volts at the resonant frequency.

The *electrostatic capacity* of the resonators varies from a few micro-micro-farads down to a small fraction of a $\mu\mu$f.

22. Quartz-Steel Resonators—For the longer wave lengths used in radio it will hardly be possible to secure sufficiently long quartz rods. The writer has used quartz up to about 4,000 m. (length of rod about 4 cm. or 1.6 inch), and beyond this has had good results with flat rods of tool steel or invar, excited to longitudinal vibration by means of small quartz plates cemented to the sides with solid shellac. The wave velocity in steel is not very different from that in quartz. For a 10,000 m. resonator, a steel rod about $95\times9\times3$ mm. ($3.71\times0.35\times0.12$ inch) is used, quartz plates about $9\times10\times1$ mm. ($0.35\times0.39\times0.04$ inch) being cemented to each side at the center, as shown in Figure 8. The steel itself forms one "coating," the quartz plates being so placed that the same polarity of each faces the steel. The other coatings are of tinfoil, to which fine wires are soldered and connected in parallel. The decrement of this combination is not very differ-

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ent from that of the larger quartz resonators. A small hook is screwed into the steel at the exact center, between the quartz plates, to serve as a suspension and as one terminal of the resonator, leaving the rod free to vibrate at its fundamental frequency. Thru the action of the transverse effect the quartz rods expand and contract when connection is made to an alternating current supply, causing an alternating condensation and rarefaction at the center of the steel rod, whereby the longitudinal vibrations are excited. The frequency is essentially that of the steel rod, and the electric reactions take place exactly as with the quartz resonators, with an intensity sufficient to produce a strong response.

FIGURE 8—Steel resonator, the exciting quartz plates having tinfoil coatings electrically connected. The hook by which the steel rod is suspended serves as the other terminal

In the earlier experiments, the steel rods had plates of quartz or Rochelle salt at their ends, but this construction proved less reliable than that with the quartz side-plates.

A photograph of a mounted quartz steel resonator for 11,000 m. is shown in Figure 9.

VII. APPLICATIONS

23. THE RESONATOR AS A WAVE LENGTH STANDARD—*1st Method*—Resonator in parallel with tuning condenser of a low-power regenerative electron tube circuit containing a telephone receiver. If the tuning condenser is varied back and forth thru the setting for resonance with the resonator, short musical clicks are heard, the ringing quality of which is an indication of the low damping of the resonator. The note is due to the fact that the resonator, when once set into vibration, generates a radio frequency current and produces beats with the oscillating current proper. If the resonator has previously been calibrated, the setting of the condenser at which the click occurs may be noted, thus establishing one point in the calibration of the circuit.

2nd Method—The above method is made more precise if in parallel with the tuning condenser there are connected a key and small capacity in series. The tuning condenser is slowly varied the key being tapped continually. When a setting is reached such that, with the key open, the resonator is set into vibration, then on closing the key a heterodyne note is heard if the auxiliary

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capacity is of the right value. The note possesses a very sharp maximum at the resonant frequency.

3rd Method—Exactly like the first two methods, save that the resonator is not in the generating circuit, but in parallel with the tuning condenser of a non-regenerative receiving circuit which is tuned to the frequency of the resonator. If the two circuits

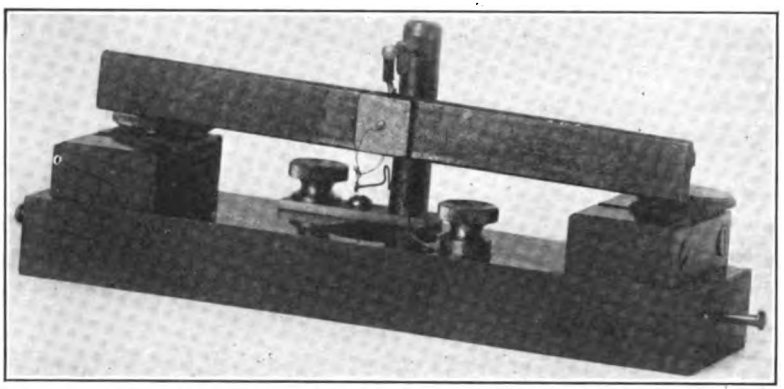

FIGURE 9—Steel resonator, excited by quartz plates at its center. Length about 10 cm. (3.9 inch), for 11,000 m. wave-length. When not in use, the resonator is unhooked and clamped to the bakelite block

are loosely coupled, a heterodyne note is heard, formed by beats between the current from the vibrating resonator and that impressed by the generating circuit. This is the most precise telephone method. For example, with a small 300-meter resonator the frequency can be determined to one part in about 5,000, while a quartz-steel resonator for 10,000 meters allows a precision of about 1 in 20,000.

Various modifications of the above methods are possible. For example, the resonator may be connected across the grid condenser or in still other parts of the generating or receiving circuit.

4th Method—Resonance indicated by ammeter or galvanometer. If the resonator is in the generating circuit, an ammeter in series with either anode or grid will give a sharp indication of resonance. Or the meter and resonator may be in a tuned circuit coupled to the generating circuit, in which case we have practically the arrangement shown in Figure 3.

5th Method—It is possible to use a resonator for the calibration of a buzzer-driven wave-meter, the receiving circuit contain-

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ing a crystal detector. Owing to the impurity of the wave the method is difficult and not generally to be recommended.

24. The Resonator as a Frequency Stabilizer

There are several methods whereby the frequency of an electron tube generating circuit can be rendered practically free from disturbing capacity effects, variations in battery voltage, and so on. All make use of one or other of the properties of the piezo-electric resonator that have already been described.

The *first method* is virtually a mechanically-tuned feed-back. A three-stage resistance-coupled amplifier is used, as shown in Figure 10. The resonator 12 has two independent pairs of metallic "coatings," one pair, 13 and 14, being connected between output anode and ground, and the other pair, 15 and 16, between input grid and ground. Any slight increase in potential of the anode 5, by altering the electric field between 13 and 14, sets the resonator into vibration. The charges thereby excited in 15 and 16 vary the potential of grid 4 with respect to the ground. This varying potential, by virtue of the amplification taking place in the system, will, if the proper coating is connected to the grid, still further increase the variations in potential of 5 and maintain the resonator in vibration. The power output is of course very small—in my tests it was only about 0.05 watt—but by the insertion of a coil at 21, or by connecting the plate 5 to the grid of another amplifier, this small power may be further amplified indefinitely. With coatings connected as shown in Figure 10, the resonator vibrates at its second harmonic, with twice the fundamental frequency, there being a loop of compression midway between each end and the center. If either pair of coatings is reversed the fundamental vibration is excited. If a quartz-steel resonator is used for this purpose, a higher degree of amplification is necessary.

Three methods will now be described, in which only a single tube is needed. In each case we require a generating circuit with the usual coils, condensers, and feed-back.

In the *second method* we use a resonator with two pairs of coatings as before, connecting one pair between anode and ground, the other across the grid condenser. If, with the resonator disconnected, the regenerative coupling is made so loose that the circuit just fails to oscillate, then when the resonator is connected it furnishes the necessary additional feed-back, and oscillations ensue, of a frequency determined solely by the resonator The circuit must be tuned approximately to the resonator, but

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small variations in the electric constants are practically without effect upon the frequency.

The *third method* makes use of the fact that the relation between resonator current i (Figure 6) and frequency is such that a resonator with one pair of coatings, connected across the grid condenser of a generating set, will stabilize the frequency to a large degree. Regenerative coupling and electrical tuning are as in the second method.

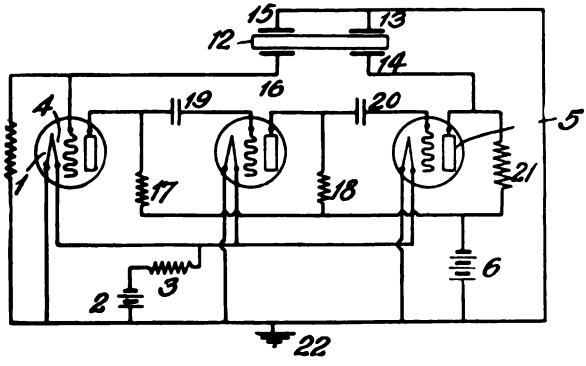

FIGURE 10—Resonator connected to three-stage amplifier, generating oscillalations with mechanically tuned feed-back

The *fourth method* is of particular interest, as it makes use of the variation of apparent capacity of the resonator with frequency. A resonator with one pair of coatings is simply connected across the tuning condenser of any generating circuit the voltage of which is not high enough to endanger the crystal. This is, in fact, precisely the connection already described in Methods 1 and 2, section 22.

In order to make the operation of this method clear, we shall suppose the circuit to be oscillating initially with a frequency below the natural frequency of the resonator. As the tuning capacity is decreased, the frequency rises, and were it not for the resonator, the curve connecting capacity with frequency would be as indicated by the line 1, 9, 2, 4, 6, 8, 7 in Figure 11. If now the resonator is present and the resonant frequency is represented by the vertical line thru 4, then shortly before this frequency is reached the resonator begins to vibrate, but since the frequency is still relatively low, the capacity C_a of the resonator is abnormally high, to compensate for which the capacity of the tuning condenser C must be made abnormally small. The curve bends down along 2, 3, becoming practically

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vertical for a considerable range of C. When this decrease in C has become greater than the maximum value of C_a, the curve springs abruptly from 3 to 8, the frequency increases by a large amount, and any further decrease in C gives rise simply to the undisturbed portion 8, 7. By similar reasoning, when C is increased the curve 7, 8, 6, 5, 9, 1, is described. The operating part of the curve for the stabilizing effect is thus either 2, 3, or 5, 6.

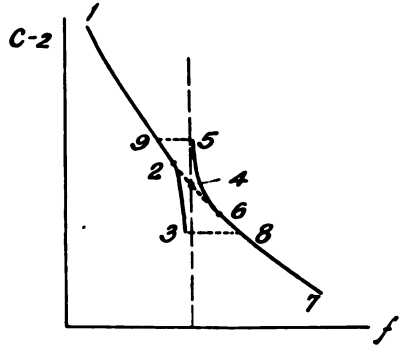

FIGURE 11—Stabilizing effect of resonator in a generating circuit. Over the portions 2, 3 and 5, 6 of the curve a large variation of C_2 produces a relatively small change in frequency

For example, a quartz plate 3.9 cm. (1.52 inch) long vibrated at a frequency of about 69,700. A change in C which, when the crystal was removed, altered the frequency by 3 percent., varied it by less than one part in 20,000 when the crystal was replaced. This resonator had coatings so small that its normal capacity was only 0.67 $\mu\mu$f.; yet when vibrating, its equivalent parallel capacity varied from $+10$ to -9 $\mu\mu$f.

25. The first method of stabilization described in section 24 suggests another possible application, namely as a *tuned mechanical coupling* between two circuits. For if the resonator is provided with two pairs of coatings, one pair being connected across a reactance in each of the circuits to be coupled, then the secondary circuit will receive energy only at the particular wave length (and, usually, certain harmonics) to which the resonator responds.

26. The nodes for the fundamental vibration or any harmonic may be detected directly by touching the crystal, while it is vibrating, with the point of a pencil. When the crystal is touched at a loop of displacement, the vibrations are easily stopped, while they are hardly affected when the contact is at a node.

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The effect of energetic vibrations may be rendered visible by viewing through a magnifying glass particles of lycopodium powder sprinkled over the edge of the resonator near its ends.

Under certain conditions a sustained musical note is heard when a resonator is connected to a generating circuit provided with a telephone. The pitch depends upon the condenser setting, as if the circuit, while oscillating at its own electrical frequency, nevertheless maintained the resonator in vibration at its mechanical frequency. The effect is especially pronounced with steel rods excited by plates of Rochelle salt.

Wesleyan University,
October 8, 1921.

SUMMARY: The general theory of piezo-electricity is summarized, and the equations applicable to quartz are stated. The "concentrated mass theory" of longitudinal vibrations in rods is then developed, and the properties of the "resonance circle" discussed. On this theoretical basis the equations for the reaction of a piezo-electric resonator upon a circuit are derived, and solved by a graphical method. From the vector diagram, important parameters, including the capacity and resistance of the resonator at any frequency, may readily be found.

The construction and operation of quartz and of quartz-steel resonators is described, and an account is given of their application as wave length standards and as frequency-stabilizing devices. Other practical applications are also suggested.

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A STUDY OF THE OSCILLATIONS OCCURRING IN THE CIRCUITS OF THE PLIOTRON*

By

James E. Ives and C. N. Hickman

(Clark University, Worcester, Massachusetts)

1. Introduction

During the months of March and April, 1918, the authors determined the nature of the currents in the circuits of a pliotron tube, for low frequencies (100 to 500 oscillations per second), by means of a Duddell oscillograph. Altho the work was interrupted by the war, and it has not been possible to complete it in the form originally intended, it is thought best to publish the results obtained.

The circuits used are shown in Figure 1, where PGF is the pliotron; B_1, the battery in the plate circuit; B_2, the filament battery; L_1 and L_3, inductances in the plate circuit; L_2 and L_4, inductances in the grid circuit, and C, a condenser. L_3 and L_4 were closely coupled. The condenser C and the coil, L_3, therefore acted as "tickling" condenser and coil, respectively. k_1 and k_2 are keys in the plate and grid circuits, respectively. Sometimes the condenser, C, was used without the coils L_3 and L_4, and sometimes they were used without the condenser.

With such an arrangement we have three principal circuits, viz.: $P\,L_3\,k_1\,L_1\,B_1\,F$, the plate circuit; $G\,L_4\,k_2\,L_2\,F$, the grid circuit; and $C\,L_3\,k_1\,L_1\,B_1\,L_2\,k_2\,L_4$, the external circuit. The oscillations were studied by inserting the oscillograph successively in each of the circuits, and obtaining oscillograms showing the current flowing for a steady oscillation and also for its rise and fall.

The Duddell oscillograph was made in the shop of the Physical Laboratory of Clark University. The pliotron tube was kindly given by the General Electric Company to Professor A. G. Webster for experimental purposes. The diameter of its bulb

* Received by the Editor, June 13, 1921.

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was about 12.6 cm. (5 inches); the dimensions of the plates about 6.0 by 4.5 cm. (2.34 by 1.76 inch), and their distance apart about one cm. (0.39 inch). The filament, midway between the plates, was at a distance of about 2 millimeters (0.078 inch) from the symmetrical grid.

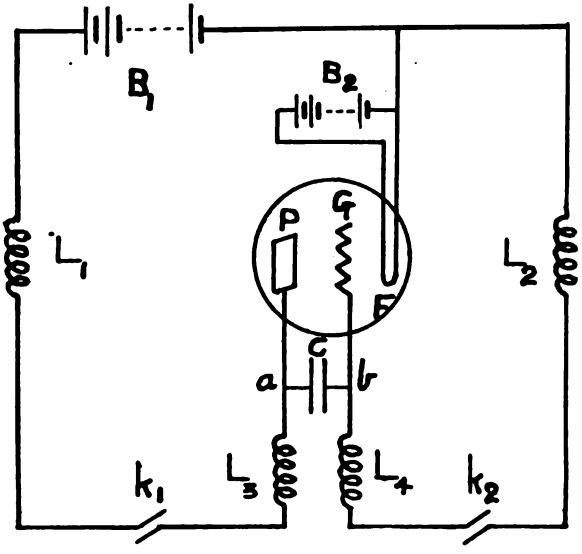

FIGURE 1—Diagram of Pliotron Circuit

The static characteristic for the tube, showing the current from the plate to the filament, for different voltages between the plate and the filament, is given in Figure 2. The current thru the filament for these values was 3.56 amperes.

The variation of the steady current from the plate to the filament as the current thru the filament is varied, when there is a difference of 71 volts between the plate and the filament, is shown in Figure 3.

On the oscillograms, the vibrations of a tuning fork, having a frequency of 101.3 vibrations a second, are shown either above or below the oscillogram. The two curves can be distinguished from each other since that of the pliotron usually has a straight line running thru it, the line of zero current.

The battery B_1, in the plate circuit, was of 80 volts and produced a direct current, when the circuits were not oscillating, of from 26 to 62 milliamperes, and a mean oscillating current,

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of from 73 to 100 milliamperes. The mean oscillating current in the grid circuit varied from 60 to 70 milliamperes. In a typical case, the direct and oscillating currents in the plate circuit were 40 and 73 milliamperes, respectively, and the oscillating current in the grid circuit was 60 milliamperes. The current thru the filament was about 3.6 amperes.

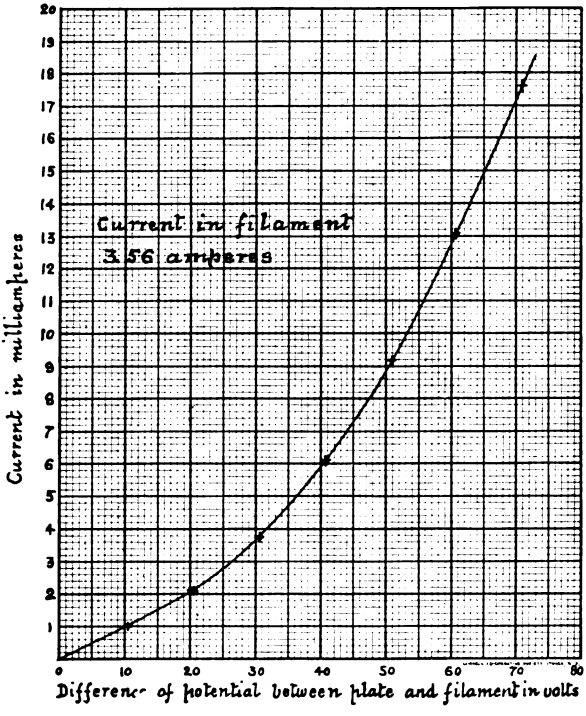

FIGURE 2—Static Characteristic for the Pliotron

2. RISE AND FALL OF THE CURRENT

To study the manner in which the oscillations begin and end in the plate and grid circuits, respectively, oscillograms 1-6 (Figure 4) were taken. For oscillograms 1-4 there were both magnetic and electrostatic coupling, and for 5 and 6, only electrostatic coupling. For 1-4, L_1 was equal to 0.143 henry; L_3, 0.147 henry; L_4, 1.95 henry; L_2, 0.203 henry, and C 0.95 microfarad. The mutual inductance of L_3 and L_4 was 0.402 henry. For 5, these values were the same except that L_3 and L_4 were taken out of their circuits and C was equal to 1.00 microfarad.

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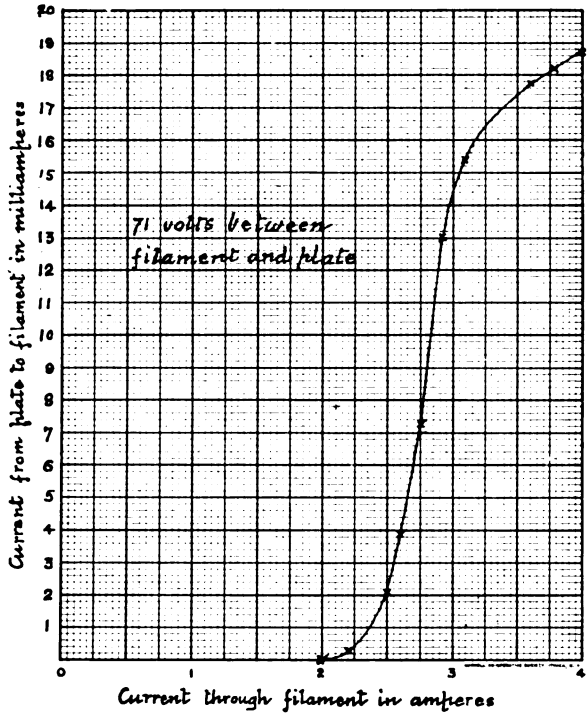
Current from plate to filament in milliamperes
71 volts between filament and plate
Current through filament in amperes

FIGURE 3—Showing Relation of Plate and Filament Currents

For 6, L_3 and L_4 were also absent; L_1 was equal to 0.210 henry; L_3, 3.25 henrys, and C, 0.50 microfarad.

Oscillograms 1 and 2, for both magnetic and electrostatic coupling, show the current in the plate circuit, the oscillograph being placed between L_3 and k_1. For 1, k_1 was closed before k_2. For, 2, k_2, was closed before k_1. If k_1 is closed before k_2, a steady direct current will be flowing in the plate circuit when k_2 is closed. If k_2 is closed before k_1, there will be no current in the grid circuit until k_1 is closed, and when this happens, both circuits will begin to oscillate immediately. Also for 1, the oscillation was *stopped* by opening k_2, and for 2, by opening k_1. It will be noticed that in these oscillograms the current is mainly positive and starts off with a positive flow.

Oscillograms 3 and 4, also for both magnetic and electrostatic coupling, show the current in the grid circuit, the oscillograph being placed between L_2 and k_2. For 3, k_1 was closed before k_2, and for 4, k_2 before k_1.

For oscillograms 5 and 6, with electrostatic coupling only,

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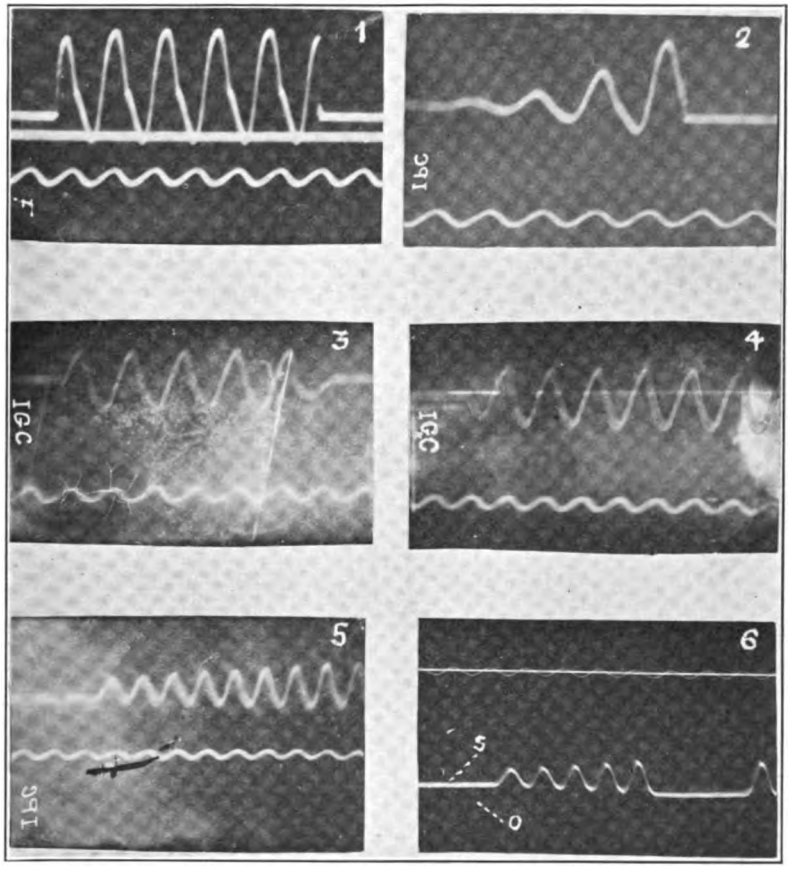

FIGURE 4—Oscillograms 1-6, Showing Rise and Fall of Current in Plate and Grid Circuits

the current builds up gradually and is not as strong as when both magnetic and electrostatic couplings are used. For 5, the oscillograph was in the plate circuit between L_3 and k_1, and k_1 was closed before k_2. For 6, the oscillograph was next to the plate. It shows the current flowing into the plate, which is seen to be all positive. The line marked *s* on the oscillogram is that for steady current, and that marked *o* is that for no current. The oscillogram shows that, in this case, the oscillating current into the plate does not return to zero for every oscillation.

3. Steady State; Electrostatic Coupling Only

Oscillograms 7-11 (Figure 5) show the current in the steady state when inductances L_3 and L_4 were taken out and there was

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therefore electrostatic coupling only. For 7-10, L_1 was equal to 0.210 henry; L_2, 3.25 henrys, and C, 0.95 microfarad.

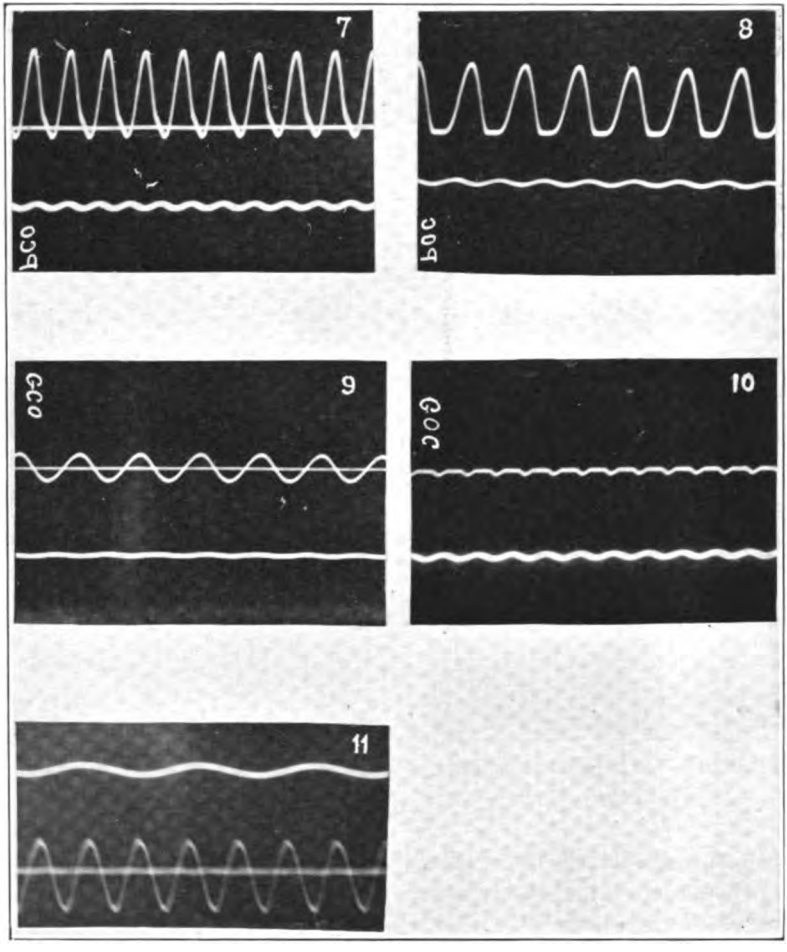

FIGURE 5—Oscillograms 7-11, Showing Current in Steady State for Electrostatic Coupling Only

For 7, the oscillograph was in the plate circuit between k_1 and L_1. It shows a large oscillating current in this circuit, mostly positive and deformed from a harmonic oscillation in a curious way. For 8, the oscillograph was next to the plate. It shows an interrupted positive current into the plate.

For 9, the oscillograph was in the grid circuit between k_2

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and L_2. It shows that the current in the main part of the grid circuit is simple harmonic. For 10, the oscillograph was placed next to the grid. It shows a small negative current into the grid.

For 11, the oscillograph was next to the condenser, C, between a and C, and shows the current flowing thru the condenser. It is seen to be simple harmonic, slightly more negative than positive. This oscillogram was taken at a different time from 7-10. C was equal to 1 microfarad, and L_1, to 0.143 henry, but no record was kept of the value of L_2.

These five curves show that, for the case of electrostatic coupling only, there is a pulsating positive current from the plate to the filament, shown in 8, which produces a harmonic current, 9, in the grid circuit. This current divides at b, a very small part of it going into the grid and the rest of it, 11, harmonic or nearly so, flowing thru the condenser. This condenser current flows back into the grid circuit by way of $a\ L_3\ k_1\ L_1\ B_1$ (see Figure 1), and, combined with 8, produces the main current, 7, of the plate circuit.

4. Steady State; Magnetic Coupling Only

Oscillograms 12-17 (Figure 6) were taken to show the current when there was magnetic coupling only; that is, when the condenser C was omitted.

For 12-15, L_1 was equal to 0.210 henry; L_3, 0.325 henry; L_4, 1.71 henry; and L_2, 0.203 henry. The mutual inductane of L_3 and L_4 was 0.505 henry.

For 12 and 13 the oscillograph was in the plate circuit; for 12 between L_3 and L_1, and for 13 next to the plate. For 14 and 15 the oscillograph was in the grid circuit; for 14 between L_4 and L_2, and for 15 next to the grid. Curve 13 shows that the pulsating positive current from the plate to the filament is nearly all positive. The small negative component added to it to form the main current, 12, of the plate circuit, may, we think, be due to the electrostatic capacity between the coupling coils L_3 and L_4. The same effect is to be noted for the grid circuit in 14 and 15. The action of the electrostatic capacity between the coupling coils in this case is of somewhat the same nature as that of the coupling condenser described in the preceding section.

For oscillograms 16 and 17, L_1 was equal to 0.143 henry; L_2, 0.203 henry; L_3, 0.147 henry, and L_4, 1.99 henry. The mutual inductance between L_3 and L_4 was 0.402 henry. 16 and 17 were taken under the same conditions except that the drum was turning faster for 17 than for 16. The conditions were much the same

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as for 12, but 16 and 17 show the presence of an oscillation of higher frequency imposed on that of the plate circuit, which the authors suppose to be due to the mutual electrostatic capacity of the coupling coils, L_3 and L_4.

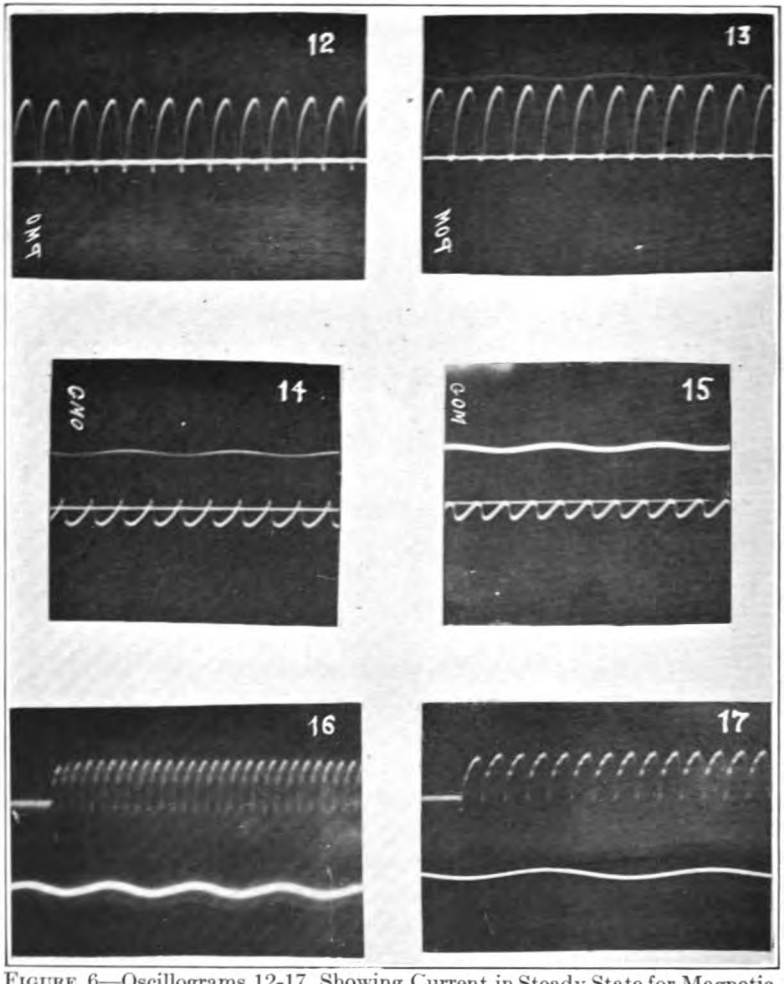

FIGURE 6—Oscillograms 12-17, Showing Current in Steady State for Magnetic Coupling Only

5. STEADY STATE; BOTH MAGNETIC AND ELECTROSTATIC COUPLING

Oscillograms 18-23 (Figure 7) give the steady current in different parts of the plate and grid circuits when there is both

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magnetic and condenser coupling between them. In this case L_1 was equal to 0.210 henry; L_3, 0.325 henry; L_4, 1.71 henry; L_2, 0.203 henry, and C, 0.95 microfarad. The mutual inductance between L_3 and L_4 was 0.505 henry.

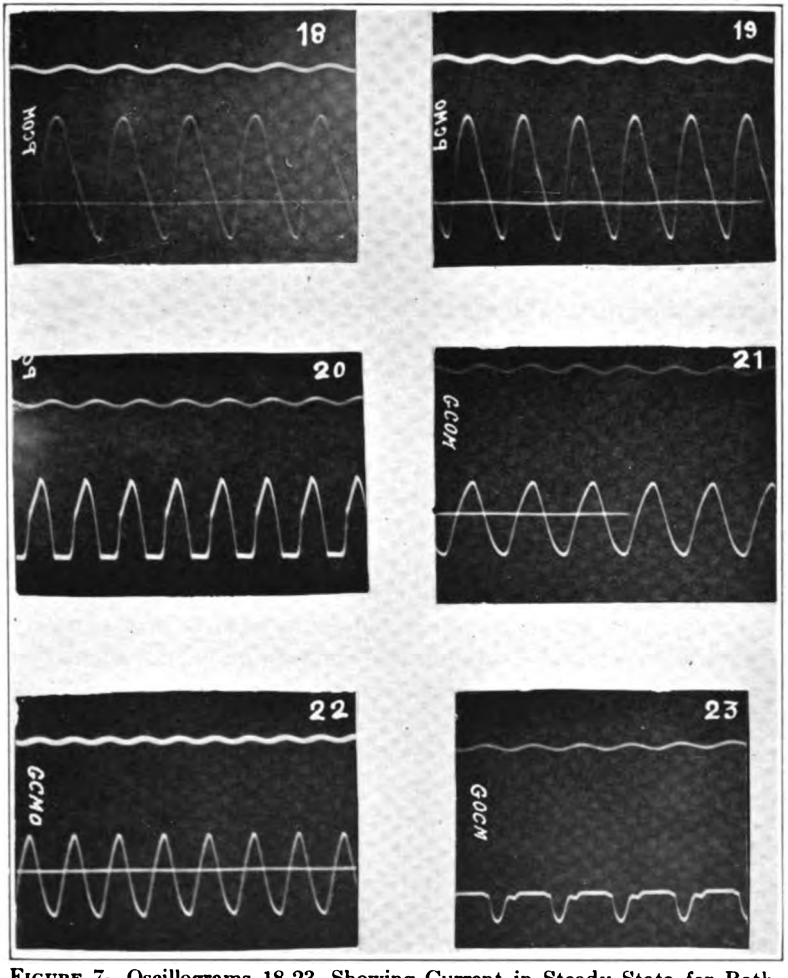

FIGURE 7—Oscillograms 18-23, Showing Current in Steady State for Both Magnetic and Electrostatic Coupling

For 18, 19, and 20 the oscillograph was in the plate circuit, and for 21, 22, and 23 in the grid circuit.

For 18 and 19, the oscillograph was placed between L_3 and a, and L_3 and k_1, respectively. The curves are alike and show the

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current flowing in the main branch of the plate circuit. It is seen that, altho it is mainly positive, it has a negative component. Its form departs strongly from a harmonic curve. For 20 the oscillograph was placed next to the plate and therefore shows the current going into it. This is seen to be all positive. The current in the main branch of the plate circuit, shown in 18 and 19, is made up of the current flowing into the plate and the current flowing into the condenser. Therefore, if 20 is subtracted from 18, we get the current flowing thru the condenser. This being oscillating will give the negative component of 18.

For 21 and 22, the oscillograph was placed between L_4 and b, and L_4 and k_2, respectively. 21 and 22 are alike and show the current in the main branch of the grid circuit. The current is nearly harmonic and is made up of that flowing into the condenser and into the grid. For 23, the oscillograph was placed next to the grid and shows the current flowing into it. It is seen to be all negative. If 23 is taken away from 21, the resultant will be the current flowing into the condenser.

6. Effect of the Mutual Capacity of the Coupling Coils

Attention has been drawn to the presence of a higher frequency imposed on the fundamental frequency of the plate circuit in oscillograms 16 and 17, and the suggestion has been made that this is due to the mutual electrostatic capacity of L_3 and L_4.

This effect would be much the same as that of a capacity shunted across L_3. To determine such an effect, a capacity of 8.3 microfarads was shunted across L_3 and oscillograms 24-29 (Figure 8) were obtained. The circuit, with its inductances and capacity, was the same as that described in the preceding section, except that for 28 and 29, the capacity C was reduced to 0.05 microfarad. For 24 the oscillograph was placed between L_3 and k_1; for 25, in the closed circuit formed by the shunting condenser and L_3; for 26, between b and L_4, and for 27, next to the grid. For 28, the oscillograph was placed in the closed circuit formed by the shunting condenser and L_3, and for 29, next to the plate. These curves show that a shunting capacity of 8.3 microfarads produces an oscillation of higher frequency than that of the fundamental of the external circuit and that the former is superimposed on the latter. Comparing these oscillograms with those given in the preceding section, we see that 24 has the same general form as 19, 26 as 21, and 29 as 20, except that the oscillation of greater frequency is superimposed on

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24, 26, and 29. Oscillograms 27 and 23, for the current going into the grid, are very much alike.

These oscillograms, therefore, show how the mutual capacity of the coupling coils L_3 and L_4 might produce the effect shown in 16 and 17.

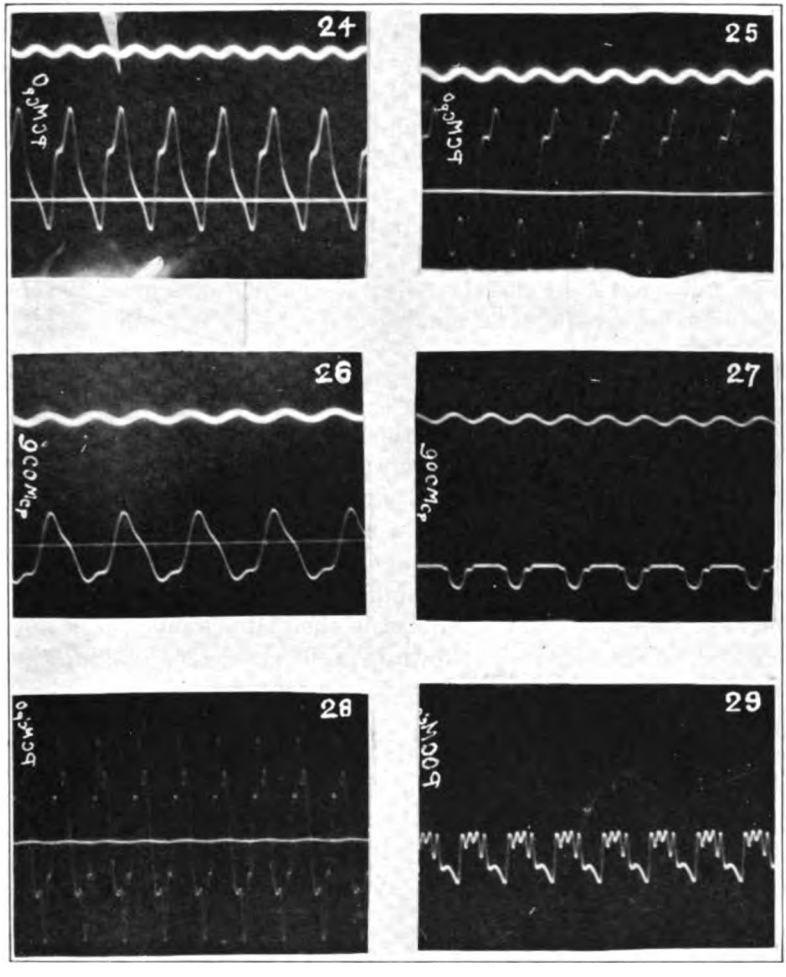

FIGURE 8—Oscillograms 24-29, Showing Effect of Condenser Shunted Across L_3

7. DISCUSSION OF RESULTS

The oscillations in the pliotron circuit shown in Figure 1 can be compared with those of the pendulum and escapement of a

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clock. The plate circuit contains a battery which supplies the energy of the oscillations just as the energy of the clock is supplied by the wound up weight or spring. The external circuit has an oscillation of a definite period, just as the pendulum has in a clock, and is kept in oscillation by the tickling coil, L_3, or the tickling condenser, C, just as the pendulum is kept in oscillation by the escapement.

It is to be noticed that in all cases the current into the grid is negative. This current into the grid produces a negative charge on it which periodically checks, or stops, the flow of electrons from the filament to the plate.

Consider the case represented by curves 12-15. Here the coupling is entirely by the coils L_3 and L_4 and there is no condenser present. Suppose that in the first place k_2 is closed and k_1 is open. Then there will be no current in either circuit. Suppose now that k_1 is closed. Then the current will grow in the plate circuit according to the law

$$i = \frac{E}{R}\left(1 - \epsilon^{-\frac{R}{L}t}\right) \qquad (1)$$

If the grid circuit is open, the plate current will grow until it reaches a steady value. If, however, the grid circuit is closed, the growing current in L_3 will create a counter electromotive force in L_4 which will produce a negative current into the grid and consequently a negative charge on it. This negative charge will reduce, or stop entirely, the flow of electrons from the filament to the plate and the current in the plate circuit will be decreased, or fall to zero, as shown in oscillogram 13. The process will then be repeated. The resistance of the plate circuit lies principally in the passage of the electrons from the hot filament to the plate, but also contains the resistances of the inductances L_1 and L_3 and of the battery B_1. It can be found approximately if we know the steady current corresponding to a given voltage of the battery B_1. For we then have

$$C = \frac{E}{R}$$

and

$$R = \frac{E}{C}$$

For our case the battery B_1 had a potential of 80 volts and produced a steady current in the plate circuit of 0.062 ampere. The equivalent resistance was, therefore, about 1,290 ohms. Since we know the inductance in the plate circuit we can calculate its time constant.

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When the flow of electrons from the filament to the plate ceases, the current in the plate circuit will decay according to the law

$$i = I\,\varepsilon^{-\frac{R}{L}t}$$

It will be seen from oscillogram 13 that the current in the plate circuit grows and decays as would be expected in a circuit containing inductance and resistance.

If both electrostatic and magnetic coupling are used, then the periodic charging and discharging of the condenser will set up an oscillating current around the external circuit $C\ L_3\ L_1\ B_1\ L_2\ L_4$. (See Figure 1.) The oscillograms obtained, 18-23, show that this current is the resultant of a harmonic current thru the condenser and the current flowing into the plate. In the same way the current in the main branch of the grid circuit is the resultant of the harmonic oscillating current thru the ocndenser and the current flowing into the grid. The currents in the main branches, both of the plate and grid circuits, are modified slightly by the mutual electrostatic capacity of the coupling coils L_3 and L_4.

When the coupling is made only by a condenser the harmonic oscillation due to the condenser is well marked, as is shown in oscillogram 9.

It is evident that there are three cases to be considered

1. Magnetic coupling only.
2. Electrostatic coupling only.
3. Combined magnetic and electrostatic coupling.

For the first case the period of the oscillation will be determined by the values of the time constants, $\frac{L'}{R'}$, and $\frac{L''}{R''}$, of the plate and grid circuits, respectively, where L' and L'', and R' and R'' are the total inductances and resistances of these two circuits.

For the second case, and also approximately for the third case, the period will be determined by the value of the capacity, C, and inductances, L_1, L_3, L_4, and L_2, in the external circuit.

If L is the total inductance and C the capacity in the external circuit, the period, T, of the oscillation in this circuit can be calculated from the formula

$$T = 2\pi\sqrt{L\,C} \qquad (3)$$

The mean period of oscillograms 7-10 was determined from the curves and the known frequency of the tuning-fork and found to be equal to 0.0118 sec. The period calculated from the

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constants of the circuit was 0.0114 sec. The calculated values are somewhat lower than the observed values, but they show that, at least for oscillations of about this frequency, and for the case of electrostatic coupling, the fundamental frequency is approximately that of the external circuit and can be calculated from the constants of this circuit.

For oscillograms 18-23, where we have both electromagnetic and electrostatic coupling, the period determined from the curves was 0.0123 sec. The calculated value was 0.0114. For oscillograms 1, 3, and 4, also cases of combined electromagnetic and electrostatic coupling, the period determined from the curves was 0.0121 sec., whereas that calculated was 0.0113 sec. In these cases, since the inductance L_3 and L_4 were very closely coupled, being in fact parts of a single large coil, the total inductance of the coil, 3.05 henrys, was taken instead of the sum of L_3 and L_4. Also, on account of their very close coupling, L_3 and L_4 probably had a large mutual electrostatic capacity, which would help to make the experimental value greater than the calculated.

The oscillograms obtained would therefore, indicate that for the cases of electrostatic, and combined magnetic and electrostatic coupling, for the oscillating circuits and frequencies used, the fundamental frequency produced by a pliotron tube can be determined, at least approximately, from formula (3) where L is the total inductance and C the total capacity of the external circuit.

Clark University,
Worcester, Massachusetts.
March 28, 1921.

SUMMARY: The currents in the grid and plate circuits of a pliotron are studied oscillographically, both for the transient conditions at the beginning of oscillations, and for the steady oscillating state. Magnetic, electric, and combined magnetic and electric couplings between the grid and plate circuits are tested. The effects obtained are explained, and the experimentally determined periods of oscillation checked against the suitably calculated values.

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A SIMPLE METHOD OF CALCULATING RADIATION RESISTANCE*

By

Fulton Cutting

(Independent Wireless Telegraph Company, New York)

The output of radio transmitting stations is the product of the input and the antenna efficiency. In designing new stations it is therefore essential to have some idea of the latter quantity in order to be able to choose the size of the generator required for a given result. Expressing this mathematically, we have the relation:

$$W_o = \frac{R_r}{R_g + R_c + R_r} W_i \qquad (1)$$

where:

W_o = output
W_i = input
R_g = ground resistance
R_c = conductor resistance
R_r = radiation resistance

For a given output the cost of a station may be given as:

$$\text{COST} = f_1(R_r) + f_2\left(\frac{1}{R_g}\right) + f_3\left(\frac{1}{R_c}\right) + f_4(W_i) \qquad (2)$$

In this equation F_1 must be determined by calculation, f_2 by experiment, f_3 by experiment (or by calculation if you know how), f_4 by ascertaining the current prices of suitable generators. Knowing these functions a radiating system and generator can be chosen to give a certain output at a minimum cost. Whether this solution will be desirable from a practical standpoint in which operating and maintenance expenses are considered, is a matter that will not be discussed here. All that is desired to be brought out is the essential importance of knowing the radiation resistance

If, for instance, the ground resistance and conductor resistance are low, and the radiation resistance at the wave length to

* Presented before The Institute of Radio Engineers, New York January 23, 1922. Received by the Editor, February 1, 1922.

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be used high, so that the antenna efficiency is over 50 per cent, any increase of radiation resistance effected by using higher towers will result in a relatively unimportant gain in antenna efficiency compared to the expense involved. If, however, the antenna efficiency is around 5 per cent, due, let us say, to unavoidably high ground resistance together with the necessity of using a very long wave, it is then well worth while increasing the radiation resistance, as the antenna efficiency and the output will be practically proportional to the radiation resistance.

The radiation resistance of an L antenna has been very ably computed by Professor Pierce. The method he uses is applicable to any shape of antenna, but it is very laborious. The present method is a modification of the doublet formula given by Hertz. It has little theoretical justification, but it is extremely simple, and checks fairly well with Pierce's results.

The doublet formula assumes that the current is uniform over the entire vertical length of the antenna. No account, moreover, is taken of the radiation from the flat top. Neglecting the radiation from the flat top is not a serious error; first, because its magnitude is small, and secondly, because its direction is such that it contributes nothing towards the electric or magnetic field in the horizontal plane. The assumption of uniform current is, of course, very far off. To correct this, it is assumed that the current decreases linearly along the antenna from maximum at the base to zero at the open end. The radiation resistance is then taken as the value given by the doublet formula multiplied by the ratio of the mean squared vertical current to the square of the current at the base.

That is:

$$R_r = 1578 \left(\frac{h}{\lambda}\right)^2 \frac{I_{eff}^2}{I^2} \qquad (3)$$

The linear current distribution is assumed, first, because it is easy to handle, and secondly, because most antennas are worked sufficiently far from their natural period to approximate this condition. A strictly linear current distribution would be obtained if the antenna were worked very far from its natural period and provided also that the capacity per unit length of the antenna remains constant along its entire length. Neither of these conditions are exactly fulfilled, but the errors introduced by the usual departure from these conditions are such as to tend to offset each other.

Let us apply (3) to an L antenna of heighth a and length b: The current distribution is shown in Figure 1:

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$$I_{eff}^2 = \frac{1}{a}\int_0^a i^2\,dx$$
$$= \frac{I^2}{a}\int_0^a \left(1 - \frac{2x}{a+b} + \frac{x^2}{(a+b)^2}\right)dx$$
$$= I^2\left[1 - \frac{a}{a+b} + \frac{1}{3}\,\frac{a^2}{(a+b)^2}\right]$$

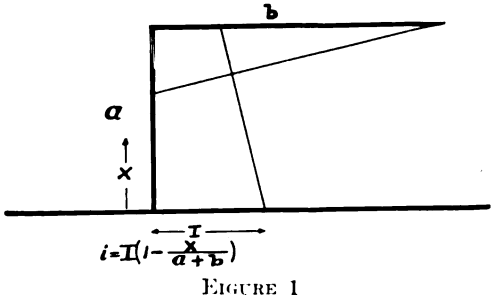

FIGURE 1

Therefore the radiation resistance is:

$$R_r = 1578\left(\frac{a}{\lambda}\right)^2\left[1 - \frac{a}{a+b} + \frac{1}{3}\,\frac{a^2}{(a+b)^2}\right] \qquad (4)$$

In cases where the flat top is as long as, or longer than the vertical portion, the last term in the brackets can be omitted without serious error. This gives the following simple formula for rough calculations:

$$R_r = 1600\left(\frac{a}{\lambda}\right)^2\left[\frac{b}{a+b}\right]$$

Using Pierce's notation:

$$\gamma = \frac{b}{a+b} \qquad \lambda_o = 4\,(a+b) = \textit{natural wave length}$$

$$R_r = 32.9\,\frac{(1-\gamma^2)}{\left(\frac{\lambda}{\lambda_o}\right)^2}\,[1+\gamma+\gamma^2]$$

Figures 2 and 3 show this expression compared with Pierce's values. The latter are shown dotted. The agreement is good for $\gamma = 0.4$, $\gamma = 0.6$, and $\gamma = 0.8$, except near the natural period. This is to be the expected, since at this point the current distribution is more nearly sinusoidal than linear, and therefore the linear assumption would give too small a value for the radiation resistance.

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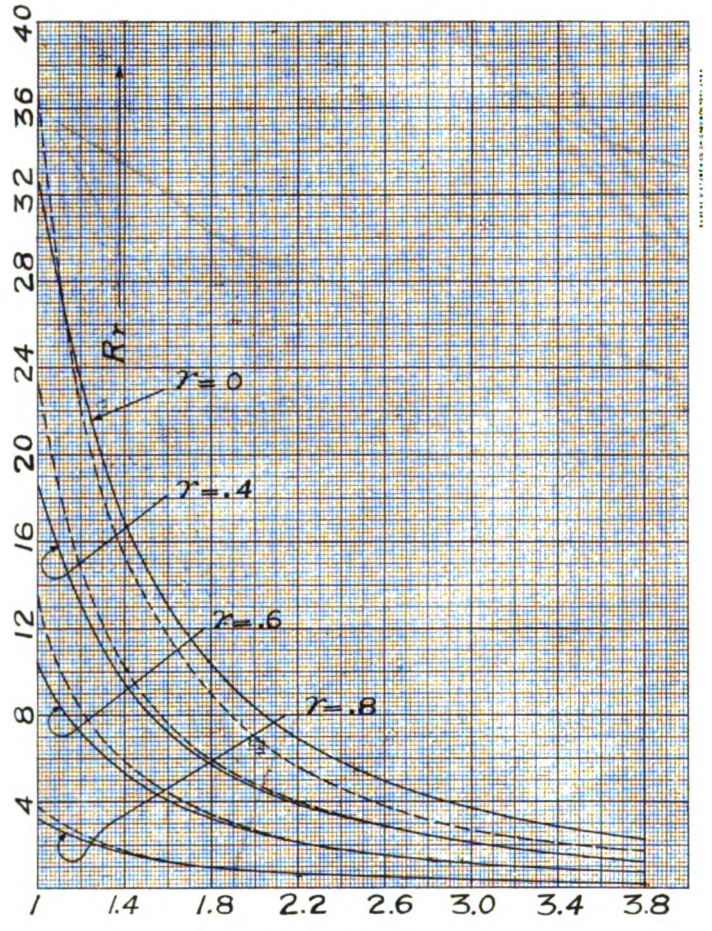

FIGURE 2

The dotted curve crosses and falls slightly below the solid curve for $\gamma = 0.4$, and markedly so for $\gamma = 0$.

Figure 4 shows the radiation resistance of the vertical portion of the antenna, calculated by Pierce's method, as compared with the total radiation resistance. The error involved in neglecting the flat top is seen to be small. Only one curve is plotted ($\gamma = 0.6$) since the maximum radiation from the flat top comes close to this point. The maximum radiation from the flat top comes when the length b is twice the height a (that is $\gamma = 1.666$).

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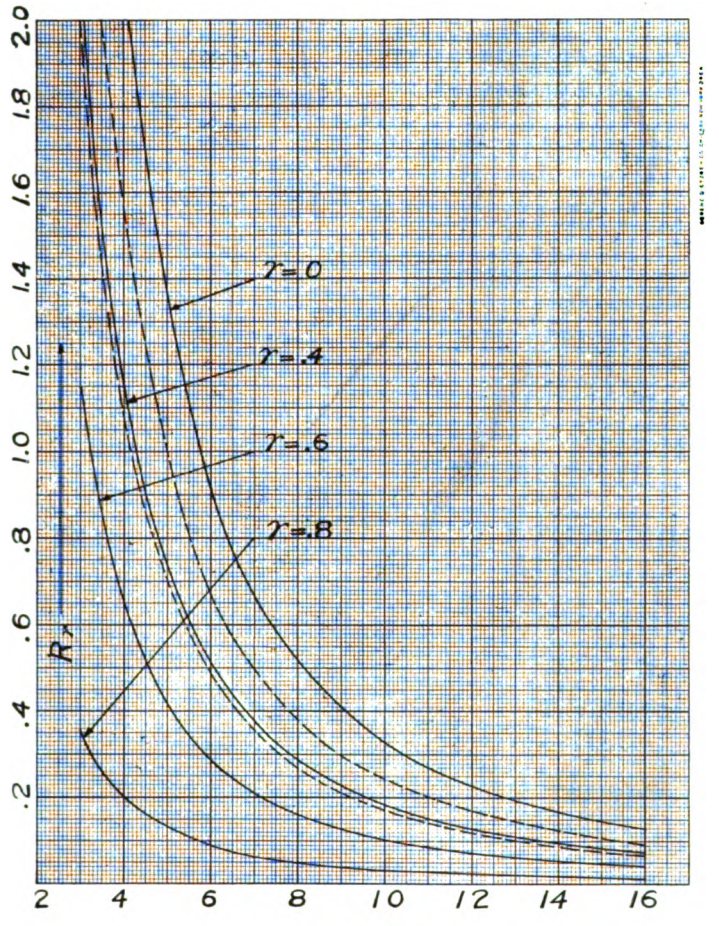

FIGURE 3

We shall now consider types of antenna different from the L. Let us take an antenna such as is shown in Figure 5.

The length to be used in the doublet formula is taken as $a+b\sin\theta$ and the effective current squared as:

$$I^2_{eff}=\frac{I^2}{a+b\sin\theta}\left[\int_o^a\left(1-\frac{x}{a+b}\right)^2dx+\left(1-\frac{a}{a+b}\right)^2\int_o^{b\sin\theta}\left(1-\frac{x}{b\sin\theta}\right)^2dx\right]$$

$$=\frac{I^2}{a+b\sin\theta}\left[a-\frac{a^2}{a+b}+\frac{a^3}{3\,(a+b)^2}+\frac{b^3\sin\theta}{3(a+b)^2}\right]$$

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Therefore:

$$R_r = 1578\,\frac{a+b\sin\theta}{\lambda^2}\left[a\left(1-\frac{a}{a+b}+\frac{1}{3}\,\frac{a^2}{(a+b)^2}+\frac{b\sin\theta}{3}\left(\frac{b}{a+b}\right)^2\right]\right. \qquad (5)$$

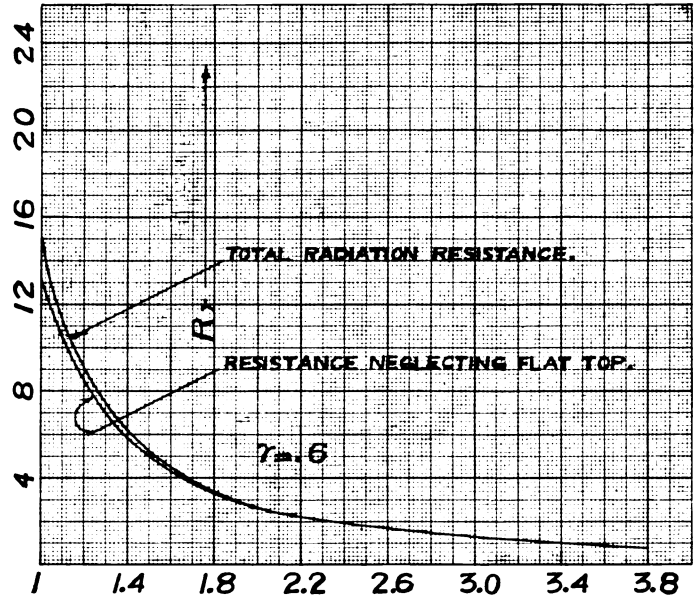

FIGURE 4

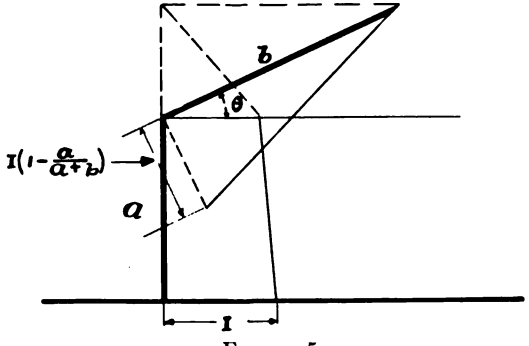

FIGURE 5

In this case the current in the flat top partly neutralizes the current in the vertical portion so that the resultant current is

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represented by the line $A\,B\,C$. The effective current squared is then:

$$I_{eff}^2 = \frac{I^2}{a}\left[\int_o^{a-b\sin\theta}\left(1-\frac{x}{a+b}\right)^2 dx + \left(1-\frac{a-b\sin\theta}{a+b}\right)^2\int_o^{b\sin\theta}\left(1-\frac{x}{b\sin\theta}\right)^2 dx\right]$$

$$R_r = 1578\,\frac{a}{\lambda^2}\left[(a-b\sin\theta)\left(1-\frac{a-b\sin\theta}{a+b}+\frac{1}{3}\left(\frac{a-b\sin\theta}{a+b}\right)^2\right) + \frac{b\sin\theta}{3}\left(\frac{b+b\sin\theta}{a+b}\right)^2\right] \qquad (6)$$

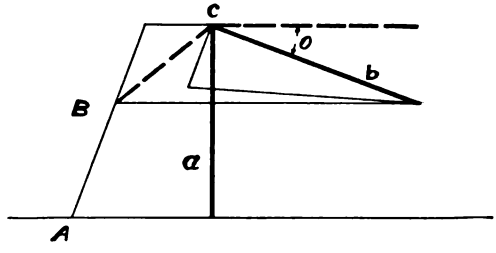

FIGURE 6

As an example of the use of these expressions, let us consider the case of an antenna which must be erected on a single mast. Three types of such an antenna are shown in Figure 7.

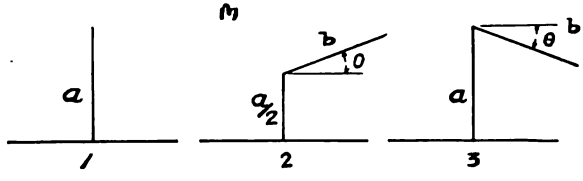

FIGURE 7

For definiteness let us take $a=b$, $\theta=\pi/6$. From (4) we have:

$$R_I = 1578\left(\frac{a}{\lambda}\right)^2(0.33)$$

From (5) we have:

$$R_{II} = 1578\left(\frac{a}{\lambda}\right)^2(0.43)$$

And from (6) we have:

$$R_{III} = 1578\left(\frac{a}{\lambda}\right)^2(0.48)$$

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We see, therefore, that Type II has a radiation resistance 28 per cent greater than Type I, and Type III a radiation resistance 44 per cent greater. Besides this, Types II and III are more advantageous than Type I owing to their larger capacity and the consequent need of less loading inductance.

Any type of antenna is subject to this simple analysis. A T antenna, for instance, can be correctly taken as an L antenna of the same length and height. The vertical current distribution is identical in both cases, the only difference being that the vertical radiation is smaller in the case of the T; this, however, is not considered in this treatment. An umbrella antenna, or in fact any antenna with regularly or irregularly arranged elevated capacity, may be treated simply by replacing the elevated capacity by an equivalent capacity arranged either as in Figure 5, or as in Figure 6.

In general, the method described here should be useful until such time as there becomes available complete radiation resistance data calculated on a firm theoretical basis. Comparative calculations of various types of antenna can be easily made, and in fact, absolute values of resistance can be obtained with a resaonable degree of approximation.

Caution, however, should be exercised in placing too great reliance in the accuracy of calculations of radiation resistance by any methods used so far. The effect of conducting masts and stays has never been taken into account, and until the effect of these can be accurately determined, radiation resistance calculations are open to a certain measure of doubt.

SUMMARY: Proceeding on the basis of the formulas for the radiation resistance of a flat-top antenna and on the assumption that the current distribution along an antenna worked at a wave length far from its fundamental is linear, there are calculated the approximate radiation resistances for various forms of antennas (flat top, upward inclined top, downward inclined top). The general application of the formulas and curves to other forms of antennas is given, together with a discussion of possible sources of error in such calculations.

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DIGEST OF UNITED STATES PATENTS RELATING TO RADIO TELEGRAPHY AND TELEPHONY*

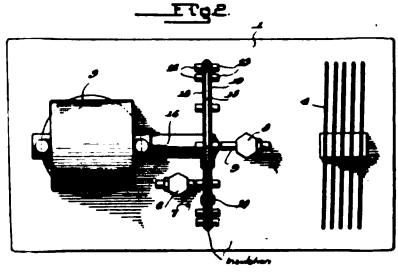
ISSUED JANUARY 3, 1922–FEBRUARY 21, 1922

BY

JOHN B. BRADY

(PATENT LAWYER, OURAY BUILDING, WASHINGTON, D. C.)

1,402,235—H. Jorgenson, filed January 20, 1920, issued January 3, 1922.



NUMBER 1,402,235—Oscillation Generator

OSCILLATION GENERATOR. This patent shows a form of transmitter unit including a transmitter inductance, a rotary spark gap and condenser arranged with minimum length of primary circuit leads to secure transmission at relatively short wave lengths.

1,402,931—P. C. Hewitt, filed March 18, 1915, issued January 10, 1922.

METHOD AND APPARATUS FOR THE PRODUCTION AND UTILIZATION OF ELECTRIC CURRENTS. This patent relates to generation of alternating currents of a definite time period from the production of periodic electric pulses of a definite time period by means of a gas, vapor or vacuum tube. The frequency of the impulses thru the pulsator is controlled by all the electrical factors of the associated circuits and oscillations generated, modulated, and transferred to an antenna system for transmission.

* Received by the Editor, March 15, 1922.

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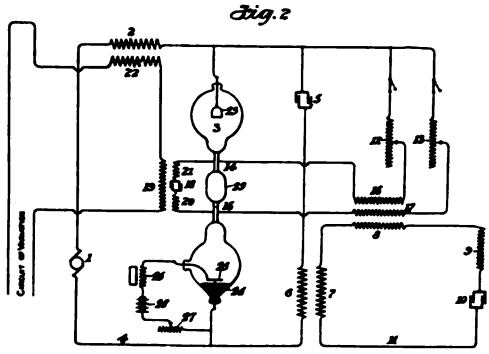
1,402,932—P. C. Hewitt, filed November 12, 1921, issued January 10, 1922.



NUMBER 1,402,932—Method of Reproducing Variations in an Electric Circuit

METHOD OF REPRODUCING VARIATIONS IN AN ELECTRIC CIRCUIT. This patent relates to a method of reproducing amplified electrical variations in a circuit employing a gas or vapor tube pulsator. Figure 2 shows the apparatus employed in a line telephone system wherein the effects of the variations produced by the operation of the telephone are reproduced in the inductances 19 and 22. Thru the action of inductances in combination with the other devices in the system and their relation to each other, the variations are reproduced or modified in the inductance 2, and being so reproduced or modified exercise an effect upon the inductance 22 and indirectly upon the inductance 19, whereby the entire telephone line is affected. At any desired point in said line, as at a local station, the variation in the line may be heard by means of a telephone and accordingly the telephone line becomes the world circuit.

1,402,933—P. C. Hewitt, filed July 6, 1916, issued January 10, 1922.

METHOD OF AND APPARATUS FOR CONTROLLING ELECTRIC CURRENT. This invention relates to a vacuum, gas or vapor tube and a circuit arrangement whereby amplification of current may be secured. Figure 3 of the patent shows a circuit arrangement wherein sound variation introduced at 20 are amplified and reproduced at 14. A magnetic field is employed to control the gas or vapor current carrying path within the tube.

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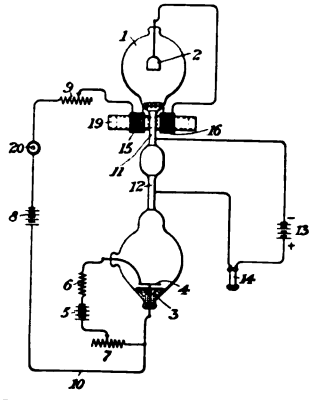
Fig. 3



NUMBER 1,402,933—Method of and Apparatus for Controlling Electric Current

1,402,991—H. A. Affel, filed October 21, 1920, issued January 10, 1922. Assigned to American Telephone and Telegraph Company.

CARRIER TELEGRAPH CIRCUIT. This invention relates to an arrangement in carrier wave telegraphy, whereby carrier signals may be translated into carrier frequencies for transmission and whereby received carrier frequencies may be translated into low frequency telegraph signals.

1,403,172—F. H. Kroger, filed July 3, 1916, issued January 10, 1922. Assigned to Westinghouse Electric and Manufacturing Company.

CONTROL OF ELECTRIC MACHINES. This patent shows a mechanical method for regulating the position of the high speed rotor with respect to the stator of a high frequency alternator.

1,403,475—H. D. Arnold, filed November 11, 1920, issued January 17, 1922. Assigned to Western Electric Company.

VACUUM-TUBE CIRCUITS. A circuit for the connection of a plurity of vacuum tubes in tandem is shown in this patent. The output circuit of one vacuum tube is provided with a path for direct current, comprising an impedance, and the input circuit of the succeeding tube is connected across a portion of the direct current path containing the impedance. A condenser is placed between the direct current circuit and the second tube to prevent

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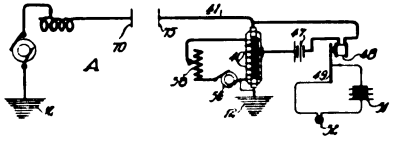
the flow of direct current, and a direct connection is also made between the input electrodes of the second tube so that a normal potential difference may be applied there-between.

1,403,640—H. J. Round and G. M. Wright, filed February 20, 1920, issued January 17, 1922. Assigned to Radio Corporation of America.

"Wireless" Telegraphy. This patent shows a circuit arrangement for a direction finder system, employing two closed loop aperiodic antennas with an inductance included in each loop circuit and a connection to ground at the midpoint of each inductance. A third inductance is coupled to the two inductances and a variable condenser shunted across the leads to the receiver. The mutual inductance between the field coils and the exploring coil is as great as possible whereby the variable condenser across the exploring coil affords all necessary tuning over a wide range.

1,403,700—F. S. McCullough, filed October 30, 1916, issued January 17. 1922. Assigned to Glenn L. Martin.



Number 1,403,700 — Apparatus for Directive Transmission of Electromagnetic Waves

Apparatus for Directive Transmission of Electromagnetic Waves. This invention has reference to an electromagnetic wave transmission and reception system in which directive capacities each consisting of a conductive flat ribbon bent upon itself in a succession of loops and arranged in the form of a parabolic reflector, are employed as antennas. The system is described for operation along a trackway or guideway where a plurality of receivers are located at intervals along the trackway or guideway, while a co-acting transmitting device may communicate selectively with the receiving devices, as it is moved along the trackway or guideway past the several receivers.

1,403,835—O. B. Blackwell, filed September 30, 1919, issued January 17, 1922. Assigned to American Telephone and Telegraph Company.

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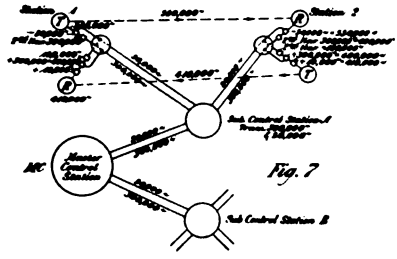

Fig. 7

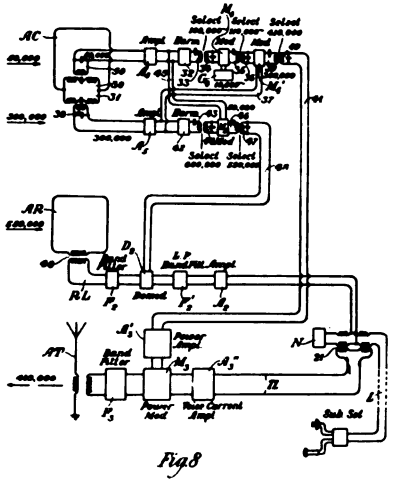

Fig8

NUMBER 1,403,835 — Frequency-Control System

FREQUENCY-CONTROL SYSTEM. This patent is directed to the organization of radio signaling systems to provide non-interfering wave lengths for stations owned and operated by different business corporations. A master station is employed to generate one or more fundamental frequencies which may be radiated to the stations of the various groups or systems, the various signaling frequencies to be used by individual stations of the groups being derived from the received fundamental frequency or frequencies. The stations are divided into groups, each group having assigned to it a definite frequency range which shall not interfere with the frequency range assigned to any other group. The fundamental frequency transmitted from the master station to the stations of the various groups is translated at the stations into the frequencies within the range assigned to the group.

1,403,841—J. R. Carson, filed September 30, 1919, issued Jan-

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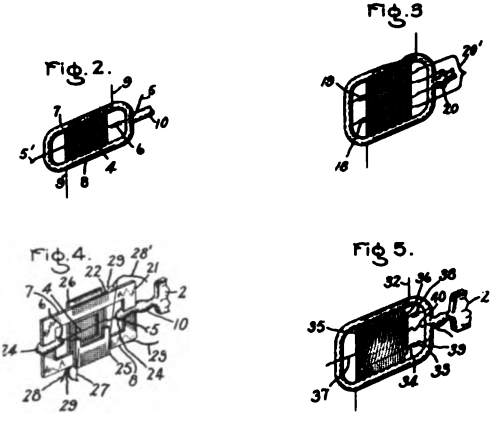
uary 17, 1922. Assigned to American Telephone and Telegraph Company.

FREQUENCY-CONTROL SYSTEM. This patent relates to a system of operating a large number of signaling stations simultaneously without interference. For this subject matter see also Patent number 1,403,835. The system comprises the organization of transmission and receiving stations whereby various signaling stations may be divided up into groups depending upon the controlling corporate business owner thereof to provide the maximum number of channels of non-interfering communication. The stations are divided into groups of inter-communicating stations, each group having assigned to it a definite frequency range which shall not interfere with the frequency ranges assigned to any other group. A master station generates a radio frequency and a relatively low frequency, too low to radiate, which modulates the radio frequency. The resultant frequencies are radiated to the stations of the groups. The small frequency difference is detected at these stations, thereby producing a low frequency. A radio frequency is selected and frequencies within the range assigned to each group produced by variously combining the high and low frequencies and harmonies of said frequencies.

REISSUE 15,278—I. Langmuir, filed April 23, 1919, issued January 31, 1922. Assigned to General Electric Company.



REISSUE 15,278—Electron-Discharge Apparatus

ELECTRON-DISCHARGE APPARATUS. This patent relates to a construction and arrangement of elements within a thermionic

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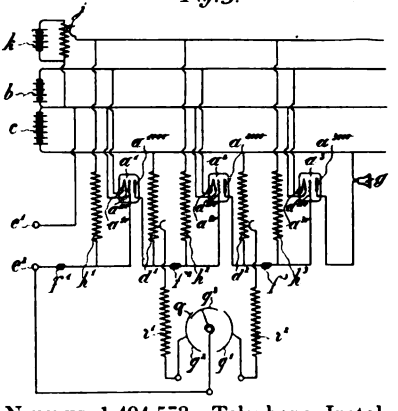
vacuum tube, wherein the cathode and grid are insulatingly supported by the same mounting.

1,404,573—L. N. Brillouin and G. A. Beauvais, filed June 13, 1917, issued January 24, 1922.

TELEPHONE INSTALLATION IN "WIRELESS" TELEGRAPHY. This patent relates to an amplifier circuit involving a plurality of vacuum tubes. The filaments of each of the tubes are heated from a common source. The plate of the first tube is connected thru a resistance to a source of plate potential. The grid of the first tube connects thru a resistance to a source of grid potential, and thru a condenser to one of the receiver terminals. The plate of the tubes of the series connect thru condensers to the grids of the succeeding tubes and the telephone receiver is included in the plate circuit of the last tube.

Fig. 3.



NUMBER 1,404,573—Telephone Installation in "Wireless" Telegraphy"

1,404,574—L. N. Brillouin, filed April 25, 1918, issued January 24, 1922.

TELEPHONE AND "WIRELESS" TELEGRAPHY INSTALLATION. This patent shows a circuit connection for a plurality of vacuum tubes. An amplifier circuit is shown, wherein the grid of the first vacuum tube is connected to one of the receiver terminals and the grids of the succeeding tube are connected to the plates of the preceding tubes in series, and a variable condenser is connected between the grid of the first tube and the plate of the last tube of the series for adjusting the circuit to heterodyne or damped wave reception.

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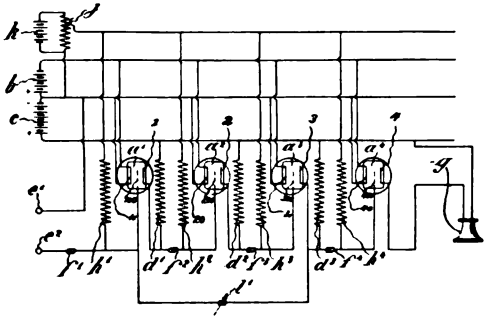
Fig 1



NUMBER 1,404,574—Telephone and "Wireless" Telegraphy Installation

1,404,726—E. F. W. Alexanderson, filed January 14, 1919, issued January 31, 1922. Assigned to General Electric Company.

REMOVING SLEET FROM ANTENNAS. The invention here is directed to a circuit arrangement for passing heating current thru an antenna of the multiple tuned type whereby to melt ice from the wires. The heating current is supplied from a transformer with its secondary connected to the antenna wires. The disconnecting switches in the individual ground leads at the intermediate tuned points are opened and switches in the individual antenna wires manipulated by the operator to pass heating current thru each pair of antenna conductors successively. The antenna system has an arrangement of cross connections which connect with only a portion of the antenna conductors and then connect with the tuned sections to ground.

1,404,756—Alfred N. Goldsmith, filed May 9, 1916, issued January 31, 1922. Assigned to General Electric Company.

SIGNALING SYSTEM. This patent shows a form of modulating circuit for a radio transmitter. The circuit shows a pliotron oscillator producing radio frequency oscillations in the primary circuit including a primary inductance. The output is modulated by varying the resistance of another pliotron from a control microphone. The second pliotron has its anode connected to the midpoint of the primary inductance and its cathode connected to ground.

1,404,799—S. E. Shackleton, filed May 31, 1919, issued January

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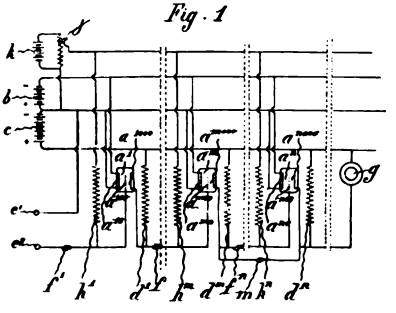
31, 1922. Assigned to American Telephone and Telegraph Company.

CURRENT-SUPPLY CIRCUIT FOR VACUUM BULBS. This patent relates to a constant current filament lighting supply system for vacuum tubes employed in telephone repeater installations with means for automatically supplying a constant filament heating current to the vacuum tubes in the event of tubes being switched out or otherwise removed from the circuit. An automatically operated polarized differentially wound relay is employed to introduce resistance into the circuit to compensate for the removal of individual vacuum tubes.

1,405,267—L. N. Brillouin and G. A. Beauvais, filed June 10, 1918, issued January 31, 1922.



NUMBER 1,405,267 — Telephone and "Wireless" Telegraphy Installation

TELEPHONE AND "WIRELESS" TELEGRAPHY INSTALLATION. This patent relates to a circuit arrangement for a vacuum tube amplifier. A plurality of vacuum tubes are employed having filaments heated from a common source of current. The plates of the respective tubes are connected thru a resistance to one pole of a source of plate circuit potential; the other pole of which is connected to one of the receiver terminals. The grid of the first tube is connected to the other receiver terminal. The grid of each of the other tubes is connected thru a condenser to the plate of the respective preceding tubes. Means are provided for modifying the amplifying effect of the equipment comprising a connection containing an impedance between the plates of two of the tubes.

1,405,905—F. W. Dunmore, filed February 4, 1921, issued February 7, 1922.

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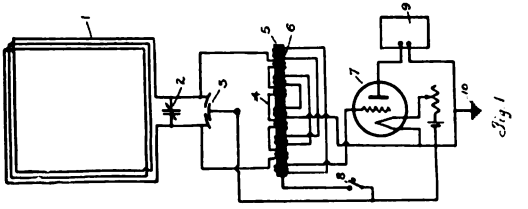
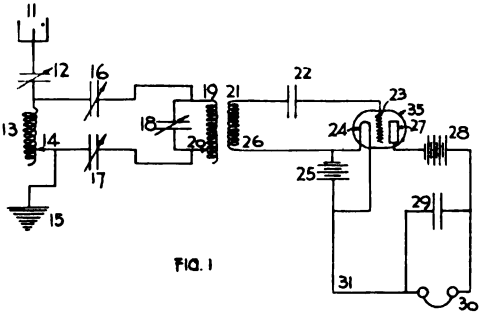


NUMBER 1,405,905—Radio Receiving Apparatus

RADIO RECEIVING APPARATUS. A loop receiving system is shown in this patent utilizing a circuit for reducing the effects of electrical dissymmetry or so-called antenna or capacity effect to ground of the loop. The object is to secure a quieter, sharper and less distorted minimum, improving the operation of the coil as an interference preventer and its accuracy as a direction finder. An iron core transformer having primary and secondary windings is employed, one connected to the terminals of the coil antenna and the other to the input circuit of a vacuum tube detector. The windings are formed in a plurality of individual sections connected in series with the primary and secondary sections alternately arranged. The iron core and filament circuit are maintained at ground potential. 3 is a balancing condenser or "Mesny compensator," which may be used in balancing what little dissymmetry in capacity to earth is not taken care of by the coupling coil. The core 5 serves a two-fold purpose. First, to couple the coil aerial to the detector and distribute the capacity effect more evenly to earth; and second, partially to bipass to earth thru the core disturbing influences such as motor and ignition noises.

1,406,442—L. Cohen, filed December 28, 1918, issued February 14, 1922.



NUMBER 1,406,442—Radio Receiving System

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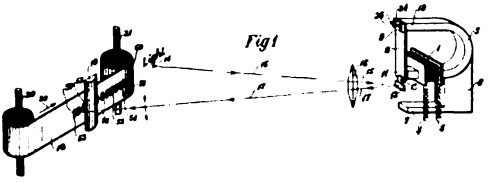
RADIO RECEIVING SYSTEM. This patent relates to a receiving circuit having high selectivity for waves of definite frequency. Static coupling is employed between the antenna ground circuit and the vacuum tube detector circuit.

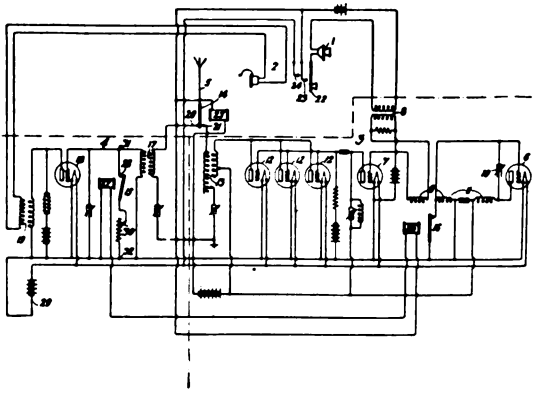
1,406,445—C. A. Culver, filed June 19, 1919, issued February 14, 1922.



NUMBER 1,406,445—Photographic Receiving Apparatus

PHOTOGRAPHIC RECEIVING APPARATUS. This patent shows a recording apparatus for radio signals wherein the received signals cause vibration of an adjustably loaded spring element carrying a mirror which directs light through a lense upon a photographic strip. The vibratory element includes a spring having a natural stiffness sufficiently low to give substantially simple harmonic vibration for small displacements when loaded.

1,406,857—R. A. Heising, filed October 26, 1916, issued February 14, 1922.



NUMBER 1,406,857—"Wireless" Signaling

"WIRELESS" SIGNALING. This patent relates to a transmitter and receiver and a protective circuit in the receiver for regulating the intensity of the side tone in the head receivers when the trans-

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mitter at the same station is being operated. Three relays, 25, 26 and 27 are employed to transfer connections from transmitting to receiving and vice versa. To disconnect the receiving system and connect the antenna to the transmitting system, it will be necessary to start the oscillator 6 and shunt the receiving system to eliminate the side-tone. These objects are attained by the use of key 22 and the three relays, for when the key 22 is pressed down, so as to make an electrical connection between the contacts 23 and 24, the circuit containing the relays and the battery 29 is closed so that the relays become energized. Switch 14 is then pulled over to contact 21, thereby connecting the transmitting system to the antenna; the switch 16 is opened, thereby breaking the shunt around part of inductance 11, thus allowing the oscillator to oscillate and to impress its oscillations on the input circuit of the modulator by means of the inductive relation between the primary and secondary of coil 9; and the switch 15 is pulled over to contact 28, thereby shunting the detector 18 so that no energy will go thru to the receiver 2. In actual practice it is sometimes desirable not to eliminate the side-tone completely, but to allow a portion of the energy ot the transmitted signals to pass thru the detector 18 to the receiver, so that the operator will know when the transmitting apparatus is working satisfactorily. If there is no resistance between points 31 and 32, there will be silence in the receiver. But there will be a desired small side-tone effect if a resistance 30 which may be variable is added to the circuit, as is shown in the drawing. By varying resistance 30, the side-tone may be regulated to any desired intensity, even to the point of complete elimination.

1,406,996—J. B. Morrill, filed September 30, 1920, issued February 21, 1922.

Electric Wave Ranging System. This patent relates to a system for determining the position of a body with respect to three fixed points which comprises ascertaining the differences in length with respect to a given electrical wave length of the direct paths from said body to said points and calculating therefrom the desired position. The system may employ other than long ether waves, that is light or radiant heat waves. It is particularly applicable to permit the pilot of an aircraft or ship to determine his location with respect to shore stations. According to this invention, electric waves are simultaneously transmitted over three courses between three fixed observing stations and the aircraft or point to be located. The velocity of propagation

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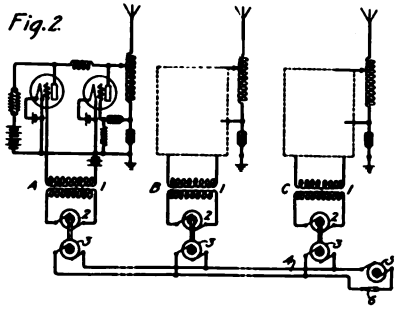
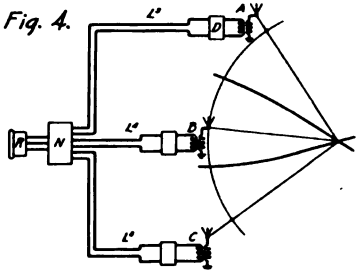
(approximately 3×10^8 meters per second) is known. The only data necessary is the difference in arrival time. Obviously, of two waves of the same phase starting at the same instant, the wave travelling the longer distance will arrive behind the wave travelling the shorter distance, and the phase difference of the two waves is a measure of the difference of their arrival time. According to the present invention the energy of the earlier arriving wave is caused to traverse a phase retarding path so as to make the phases of the two waves the same, as indicated by a null indication obtained when their energies are opposed to each other in a differential indicator. A feature of the invention consists in transmitting the energies over the different courses, as carrier waves of correspondingly different frequencies, to enable them to be readily separated at the receiver. In order to secure an audible note, so as to determine when a phase balance has been secured, each of these carrier waves may be modulated in accordance with the same audible frequency wave.





NUMBER 1,406,996 — Electric Wave Ranging System

1,407,103—F. K. Vreeland, filed February 17, 1917, issued February 21, 1922.

RECEIVING SYSTEM FOR RADIO TELEGRAPHY AND TELEPHONY. This patent is directed to a receiving circuit for the elimination

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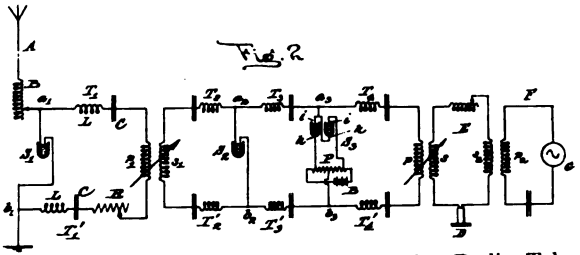
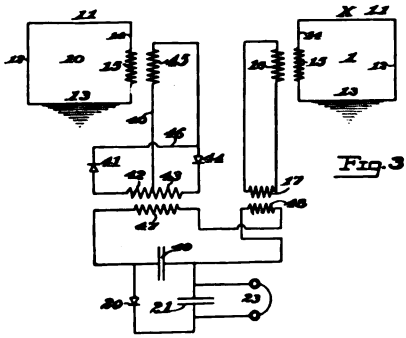


NUMBER 1,407,103—Receiving System for Radio Telegraphy and Telephony

of interference by strays or static disturbances. The circuit employs electrolytic cells as "intensity selectors" which discriminate between the strong static impulses and feebler signal impulses, permitting the passage of the feebler impulses but diminishing or diverting the stronger disturbances.

1,407,205—R. H. Marriott, filed December 26, 1916, issued February 21, 1922.



NUMBER 1,407,205—Radio Receiving System

RADIO RECEIVING SYSTEM. This invention relates to a circuit for a radio receiver arranged to neutralize or dissipate the effects of undesirable currents. These undesirable currents cause the production of two currents of definite but different periods. One of these currents is transformed into a current of the same period as the other and then, by combining these two currents into a current of the same period as the other, both are neutralized, leaving only the effects produced by the periodic signal current which it is desired to translate at the receiver.

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PROCEEDINGS OF
The Institute of Radio Engineers

Volume 10 JUNE, 1922 Number 3

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THE MONTHLY AVERAGES OF SIGNAL STRENGTH OF NAUEN IN WASHINGTON, 1915-1921
AND
THE MONTHLY AVERAGES OF ATMOSPHERIC DISTURBANCES IN WASHINGTON, 1918-1921*

By
L. W. Austin
(United States Naval Radio Laboratory, Washington, D. C.)

(Communication from the International Union for Scientific Radio Telegraphy)

Daily observations on the electric field intensity (electric gradient) in Washington, produced by the German high power station at Nauen have been made at the U. S. Naval Radio Research Laboratory at The Bureau of Standards since 1915, with only slight interruptions. The wave length is 12,500 m. The observations up to the present have been made by the well-known audibility method (Proceedings of The Institute of Radio Engineers, volume 5, page 239, 1917). The accuracy of the single audibility observations is about twenty per cent. under good conditions, while under the influence of heavy atmospheric disturbances or noise in the laboratory the apparent audibility may be reduced to one half or less of the true value.

Observations on the strength of the atmospheric disturbances or static have been made twice daily since early in 1918 between the wave lengths of 3,000 and 18,000 meters. The audibility of the disturbances was assumed to be the setting of the audibility meter for which the disturbances could be heard three times in ten seconds. Here 100 audibility corresponds roughly to 10 microvolts per meter field intensity. This method takes no account of the different types of disturbances, but a record is now kept of the occurrence of the crashing non-directional type which seems to have a different source from the more common rumbling variety. The single disturbance measurements are probably accurate to about thirty or forty per cent.

Sufficient data have now been collected to make it seem worth while to publish the results in the form of curves representing the monthly averages with some sample curves of single months showing the changes from day to day.

*Received by the Editor, April 14th, 1922.

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Up to 1921, the receiving set was calibrated by signals of known strength in the laboratory (PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS, volume 5, page 239, 1917). Since early in that year calibration has been made by comparison with signals of known intensity from a station more than a wave length away with a few milliamperes in the antenna.

With the end of 1921, audibility measurements at the laboratory have been given up, at least for the measurement of signals, and have been replaced by a comparison method of measuring the current in the telephones by impressing a known alternating electromotive force of the frequency of the signals on the telephone circuit.

Figure 1 shows the monthly averages of Nauen. The Nauen antenna current, according to present information, was about 240 amperes from July, 1915, to August, 1917; 320 amperes from August, 1917, to November, 1919; and since then about 380 amperes. The curves do not show any regular increase corresponding to this increase in current. It will be seen that during 1916 and 1917 the curve is high and irregular. During 1918 and 1919, lower and more regular, and during 1920 and 1921, higher and relatively regular. If the observations are correct, we must assume that the atmospheric conditions have, to a large extent, masked the effects of the change of transmitting power. The monthly averages of the atmospheric disturbances at 12,000 meters (Figure 2) show 1918 and 1919 to have been years of weak disturbance, compared with 1920 and 1921. It is also known that the summer of 1917 showed extremely heavy disturbances in the afternoons, altho no complete record was kept during that year (PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS, volume 9, page 28, 1921.) On a number of days in August the audibilities, brought within the range of the audibility meter by inserting resistance in the antenna, showed a strength of between 10,000 and 15,000 audibility. This all indicates that the years of strong disturbance intensity are also years of strong signal intensity. Of course, it may be charged that the differences are due to errors of calibration in our receiving apparatus, altho, in view of the efforts for accuracy, it does not seem possible that errors of this amount could exist. With our present method of measurement this would, of course, be out of the question.

SUMMARY: The monthly averages of the signal strength of Nauen in Washington from 1915 to 1921, and the monthly averages of atmospheric disturbances, in Washington during 1918-1921, are given graphically. The methods of measurement used are described and analyzed.

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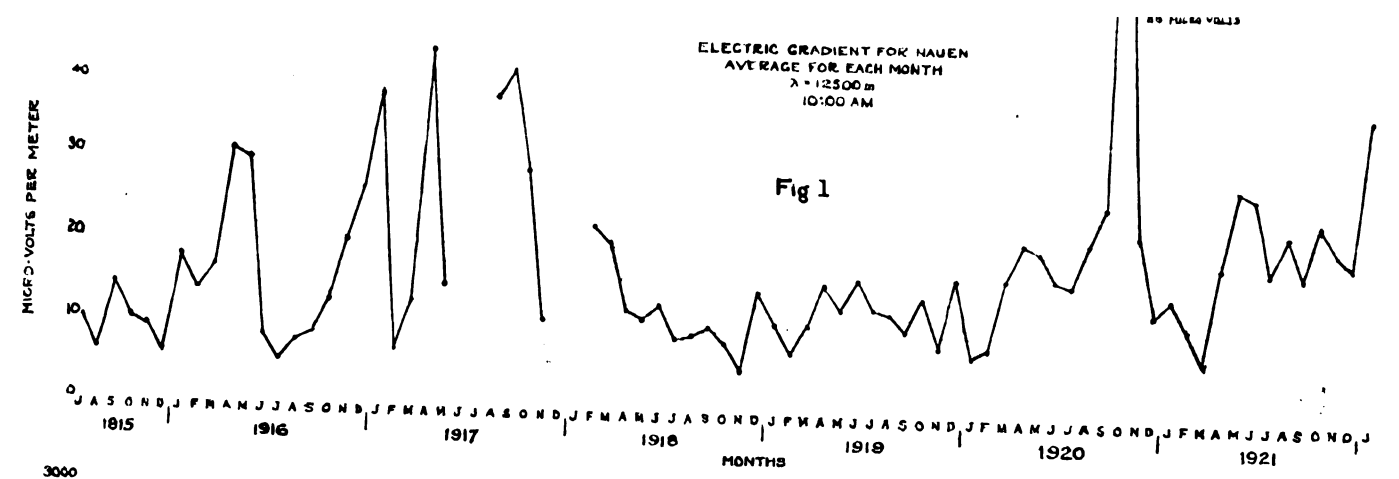
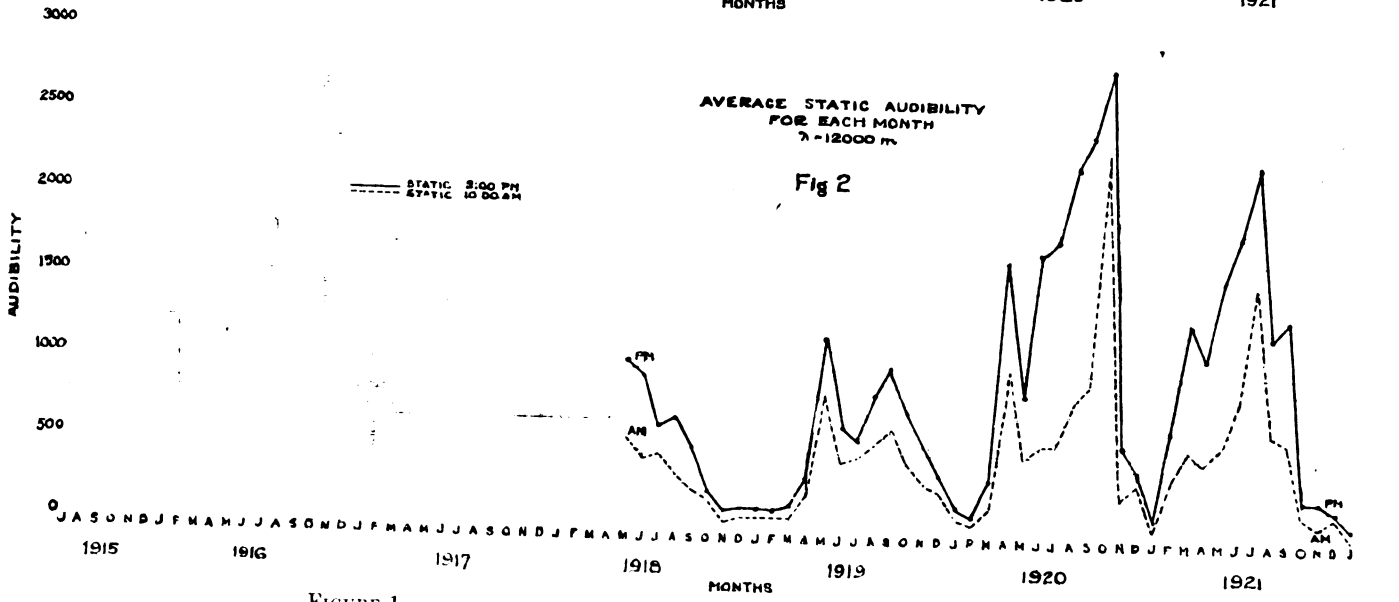

ELECTRIC GRADIENT FOR NAUEN
AVERAGE FOR EACH MONTH
λ = 12500 m
10:00 AM
Fig 1
MICRO-VOLTS PER METER
0
10
20
30
40
J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J
1915
1916
1917
1918
1919
1920
1921
MONTHS


AVERAGE STATIC AUDIBILITY
FOR EACH MONTH
λ = 12000 m
Fig 2
STATIC 3:00 PM
STATIC 10:00 AM
AUDIBILITY
0
500
1000
1500
2000
2500
3000
PM
AM
J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J
1915
1916
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1918
1919
1920
1921
MONTHS

FIGURE 1

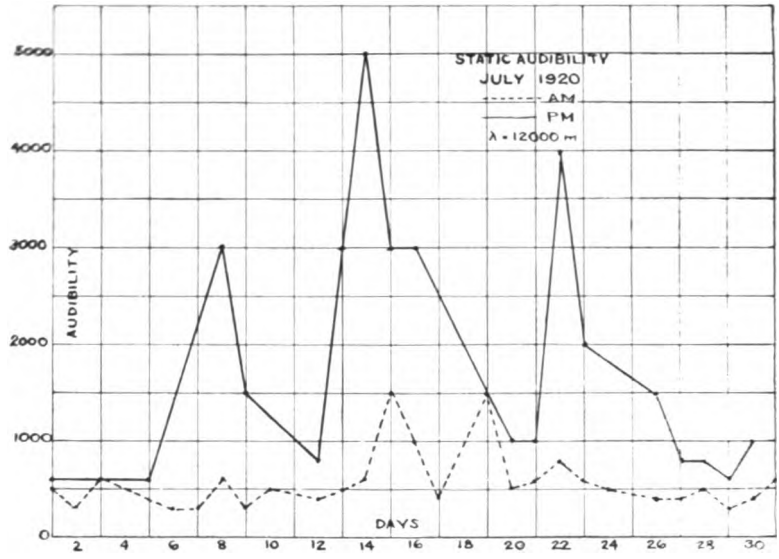

FIGURE 3

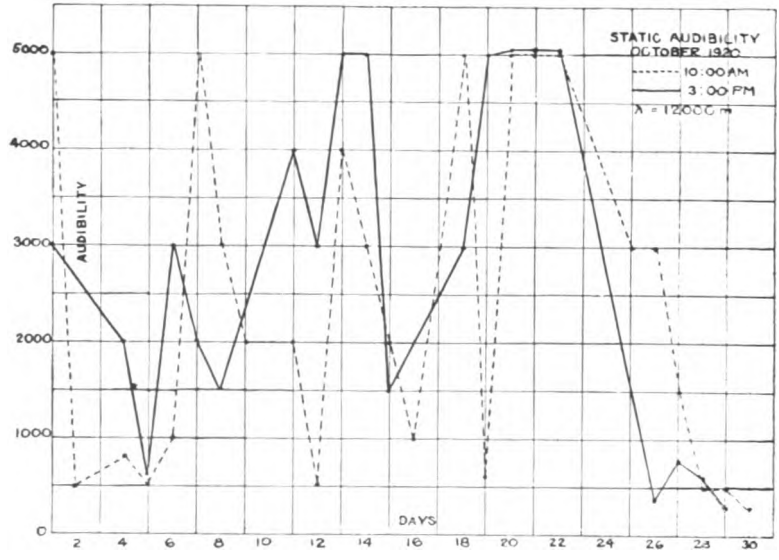

FIGURE 4

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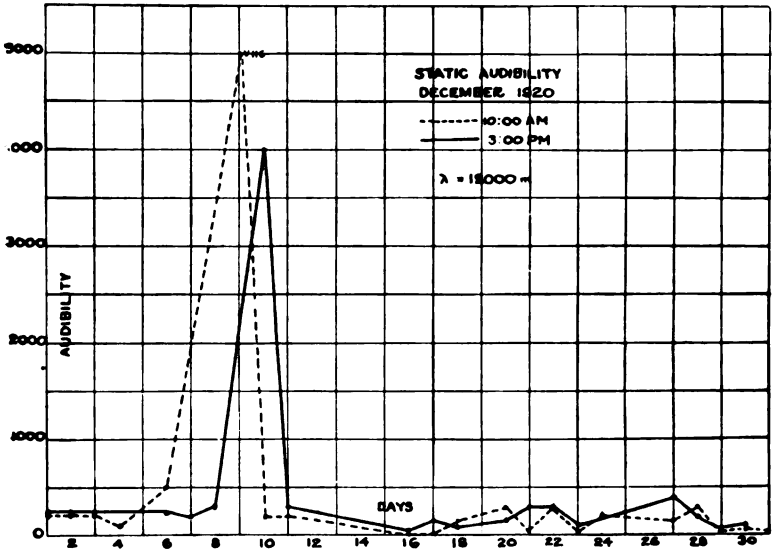

FIGURE 5

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RECEPTION MEASUREMENTS AT NAVAL RADIO RESEARCH LABORATORY, WASHINGTON*

By

L. W. Austin

(United States Naval Radio Laboratory, Washington, D. C.)

(Communication from the International Union for Scientific Radio Telegraphy)

The observations in the tables were taken by comparison of the telephone current due to the signal with that due to a known audio frequency electromotive force impressed on the telephone terminals. The signals were received on an antenna having an effective height of 15.5 meters (51 feet). The receiver was of the inductively back-coupled autodyne type without amplification. The system was calibrated frequently by receiving feeble signals of known intensity from the Washington Navy Yard and from the Naval Air Station.

At the same time that the U. S. R. I. (International Union for Scientific Radio Telegraphy) tests Table I were being carried out in the afternoon, measurements were also made on Nauen, Lyons, and Lafayette in the forenoon, Table II. In general, the forenoon is preferable in Washington for the measurement of European signals, on account of the fact that there is daylight over the whole path. In summer the signals would be generally two to ten times stronger at 10 A.M. than at 3 P.M.

Data for calculation.

	Lafayette	Lyons	Nauen
Sending current..... I_s	480 amp.	250 amp.	380 amp.
Sending height..... h_1	170 meters	150 meters	150 meters
Wave length..... λ	23,400 meters	15,000 meters	12,500 meters
Distance..... d	6,160 Km.	6,460 Km.	6,650 Km.
$\epsilon - Ad$	0.148	0.081	0.059
Receiving resistance. R	94 ohms	56 ohms	54 ohms

Electric field intensity

$$E\,(calculated) = 120\pi \frac{I_s h_1}{\lambda d} e^{\frac{-0.0000475d}{\sqrt{\lambda}}}$$

(*volts, meters, amperes, ohms.*)

$$E\,(observed) = \frac{B I_t \sqrt{R}}{h_2}$$

*Received by the Editor, April 14, 1922.

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I_t = telephone current.

B = constant = 180 for our apparatus.

h_e = effective height = 15.5 m.

9:30 TO 11:30 A.M. WASHINGTON TIME

Date	Lafayette		Lyons		Nauen	
	Aud.	Volts/Meter	Aud.	Volts/Meter	Aud.	Volts/Meter
Feb. 17	....	....	215	$19.0 \cdot 10^{-6}$	470	$41.0 \cdot 10^{-6}$
18	....	....	172	15.0	385	34.0
20	640	$75.0 \cdot 10^{-6}$	215	19.0	430	38.0
21	....	....	300	26.5	....	....
23	470	55.0	260	23.0	385	34.0
24	430	50.0	....	....	430	38.0
25	385	45.0	215	19.0	300	26.5
27	568	65.0	172	15.0	260	22.5
28	515	60.0	215	19.0	300	26.5
Mar. 1	515	60.0	260	23.0	430	38.0
2	470	55.0	215	19.0	340	30.0
3	493	58.0	172	15.0	300	26.5
4	430	50.0	172	15.0	300	26.5
6	515	60.0	260	23.0	385	34.0
7	430	50.0	....	....	260	22.5
8	600	70.0	300	26.5	385	34.0
9	770	90.0	260	23.0	430	38.0
10	770	90.0	215	19.0	430	38.0
11	568	65.0	....	....	300	26.5
13	430	50.0	260	23.0	340	30.0
14	515	60.0	260	23.0	385	34.0
15	600	70.0	215	19.0	340	30.0
16	640	75.0	260	23.0	385	34.0
17	640	75.0	....	....	515	45.0
18	568	65.0	215	19.0	300	26.5
20	385	45.0	....	....	....	....
21	430	50.0	130	11.5	260	22.5
22	568	65.0	260	23.0	340	30.0
23	600	70.0	340	30.0	515	45.0
24	770	90.0	340	30.0	560	49.0
25	430	50.0	300	26.5	385	34.0
27	515	60.0	215	19.0	300	26.5
28	....	....	260	23.0	385	34.0
29	600	70.0	385	34.0	770	68.0
30	568	65.0	260	23.0	385	34.0
31	470	55.0	....	....	90	7.8
Average	542	$63.0 \cdot 10^{-6}$	244	$21.5 \cdot 10^{-6}$	375	$33.1 \cdot 10^{-6}$

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3:00 P.M. WASHINGTON TIME

Date	Lafayette U.R.S.I. Aud.	Lafayette U.R.S.I. Volts/Meter	Lyons Aud.	Lyons Volts/Meter	Nauen Aud.	Nauen Volts/Meter
Feb. 17	470	$55.0 \cdot 10^{-6}$	172	$15.0 \cdot 10^{-6}$	430	$38.0 \cdot 10^{-6}$
18	730	85.0	....	....	....	....
20	685	80.0	260	23.0	340	30.0
21	515	60.0	....	....	....	....
23	470	55.0	....	....	....	....
24	515	60.0	....	....	....	....
25	568	65.0	215	19.0	....	....
27	470	55.0	....	....	....	....
28	430	50.0	....	....	....	....
Mar. 1	515	60.0	....	....	....	....
2	568	65.0	....	....	....	....
3	430	50.0	215	19.0	300	26.5
4	340	40.0	....	....	....	....
6	470	55.0	172	15.0	300	26.5
7	385	45.0	....	....	....	....
8	730	85.0	260	23.0	385	34.0
9	430	50.0	....	....	....	....
10	730	85.0	260	23.0	340	30.0
11	515	60.0	....	....	....	....
13	470	55.0	215	19.0	340	30.0
14	470	55.0	....	....	....	....
15	385	45.0	215	19.0	430	38.0
16	515	60.0	215	19.0	300	26.5
17	600	70.0	130	11.5	215	19.0
18	730	85.0	....	....	....	....
20	515	75.0	....	....	....	....
21	470	55.0	215	19.0	300	26.5
22	430	50.0	215	19.0	300	26.5
23	470	55.0	....	....	....	....
24	430	50.0	260	23.0	430	38.0
27	470	55.0	215	19.0	340	30.0
28	300	35.0	215	19.0	300	26.5
29	340	40.0	....	....	340	30.0
30	770	90.0	....	....	....	....
31	340	40.0	....	....	150	13.0
Average	505	$59.3 \cdot 10^{-6}$	215	$19.0 \cdot 10^{-6}$	326	$28.8 \cdot 10^{-6}$

SUMMARY: Signal intensity using an autodyne receiver was measured by comparison of telephone current with that produced by a known audio frequency electromotive force. The signals from Bordeaux, Lyons, and Nauen were measured during February and March, 1922, at approximately 10 A.M. and 3 P.M. The results are given.

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THE DIRECTION AND INTENSITY OF WAVES FROM EUROPEAN STATIONS*

By
Greenleaf W. Pickard

(Consulting Engineer, The Wireless Specialty Apparatus Company, Boston, Massachusetts)

It has been known for over thirteen years that the apparent bearing of a distant station, as taken by the radio compass, often differs widely from the true bearing. The writer discovered in his early work with the coil aerial that unsymmetrically distributed conductors on the earth's surface, such as buildings, trees, and bodies of waters, often caused large deviations from the true bearing, even approaching 90° at certain receiving points, particularly when these were near a river. In an account of these observations published in 1908[1] is given a map showing the result of a radio compass survey around a transmitting station, which is reproduced in Figure 1.

The heavy black lines on this map are the projections of the compass coil when in the minimum or null position, and the effect of a stream of water is strikingly shown at the right of the map, near the junction of the Powow and Merrimack Rivers.

The extended use of the radio compass during the war has not only confirmed the writer's early observations, but has brought to light another variety of error, apparently not due to fixed obstructions, but varying from day to day, hour to hour and even from minute to minute. These variations, which for moderate distances and wave lengths are of the order of a few degrees, appear to increase with wave length and to some extent with the distance of transmission, until with the waves involved in trans-Atlantic working there have been reported deviations of over 45°. The bibliography of this subject, at least so far as the publication of actual observations is concerned, is not only lamentably limited, but is practically entirely confined to the past two years, the first publication I have so far found of actual determinations being by Taylor in 1919[2]. This observer, with a compensated receiving coil at Washington, D. C., found large

* Received by the Editor, October 25, 1921.

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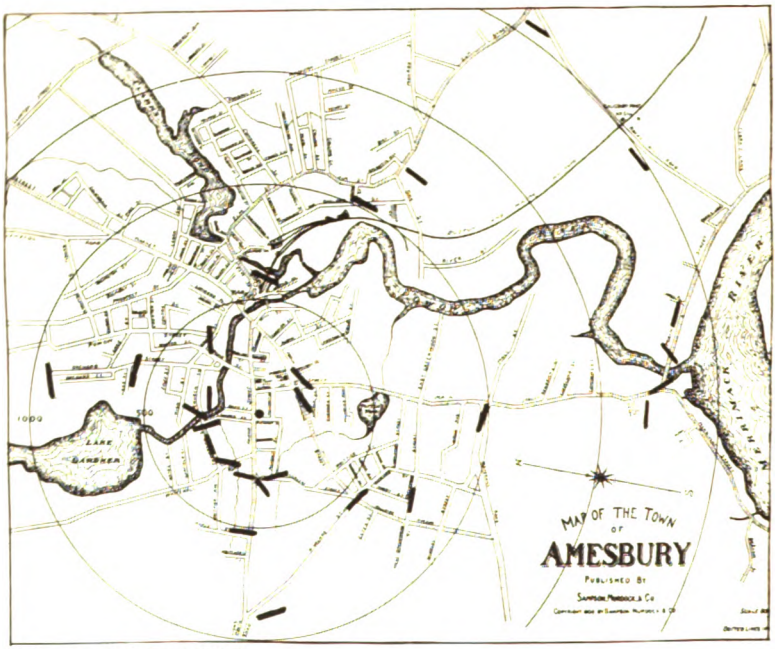
deviations in the waves from Annapolis, New Brunswick, and Sayville, in one instance approximating 90°, and also that there were times when no definite minimum or null point could be found. The transmission was in all cases entirely overland, and the distances ranged from 55 to 280 kilometers (34 to 174 miles).



By Permission of Sampson & Murdock

FIGURE 1

Kingsley and Sobey,[3] with goniometric stations at three widely separated inland points, Houlton, Maine, Tucson, Arizona, and McAllen, Texas, also found large deviations, in one instance over 56°, and not infrequent instances when no definite minimum could be found. The greater part of their observations were taken on waves which had travelled entirely over land, and as their stations were all inland, all of their reception involved transmission over a considerable stretch of land at the receiving end. Fessenden[4] states that errors of 45° are sometimes found, and that over water and parallel to a coast line the waves will bend inland. He also says that the true direction can be determined by taking observations on different wave lengths; if they agree, the apparent bearing is the true one. The writer's observations this summer, given below, are hardly in accord with this state-

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ment. European stations with wave lengths of 12.6 and 23.4 kilometers having been found to vary simultaneously from the true bearing by over ten degrees. The remainder of the brief bibliography of this subject is given at the end of this paper. On one point, at least, there is a practical consensus of opinion: almost to a man the various writers lay the errors on the broad shoulders of the Heaviside Layer.

During the spring and summer of 1918, the writer had occasion to determine the apparent bearing of the European stations from Otter Cliffs, Maine. A number of observations were made with a large solenoidal coil, and no deviation greater than ten degrees from the true bearing was found. During the winter of 1918-1919, and at intervals during the summer of 1919, a series of bearings were taken on Nauen, Germany, from the roof of the Board of Trade Building, Boston, Massachusetts, in which a large constant deviation was observed, apparently due to the proximity of the Custom House Tower, a steel frame structure some 160 meters (524 feet) high, and about 100 meters (328 feet) due east from the receiving point. Nauen's apparent bearing was also due east, an error of over 45°.

During the month of August, 1921, the writer undertook a prolonged series of radio compass bearings of European and other stations from a receiving point located at Seabrook Beach, New Hampshire, North 42° 52′ 24″, and West 70° 49′ 4″. Seabrook Beach is a low, sandy strip of land, some three meters (10 feet) above high tide level, running nearly north and south between the Atlantic Ocean on the east, and a wide salt marsh on the west, and is apparently, at least in so far as local obstructions are concerned, an ideal receiving point. Until one has plotted a number of great circle bearings, it is difficult to appreciate the fact that there is no point on the Atlantic coast of the United States, save only the tip of Florida, which is entirely free from obstacles in the path of the waves from European stations. In general, a great circle passing thru the chosen receiving point and such a station as Nauen, Germany, will run grazingly northeast along our coast, and will cut thru parts of Nova Scotia and Newfoundland, as is shown in Figure 2, which gives the great circles passing thru Seabrook Beach, Nauen, Germany, and Bordeaux, France. In this Figure is also shown the great circle passing thru Seabrook Beach and San Diego, California. It will be noted that the great circle bearing of San Diego from Seabrook is nearly due west, and the waves from the station at San Diego, if they followed the great circle, would pass thru the gap between

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the Catskill mountains to the south and the foothills of the White Mountains to the north, some 150 kilometers (93 miles) west of Seabrook. Actually, as will be seen from the observations below, the waves arrived from San Diego with a mean apparent bearing of over ten degrees to the north of the true direction, while the waves from Nauen and Bordeaux came in on Seabrook with a mean deviation from true bearing of four degrees to the east.

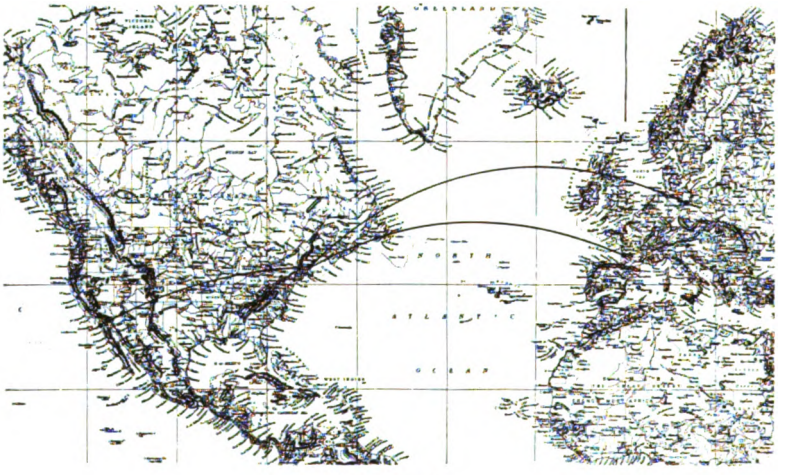

FIGURE 2

At a point fifty meters (164 feet) to the west of high water mark at Seabrook Beach, a solenoidal compass coil was erected, wound on a square frame 305 centimeters (10 feet) on a side, with twenty turns of 7 strands of number 22 copper wire,* spaced 2.5 centimeters (1 inch) apart, and supported by bakelite combs at the four corners of the frame. This loop, with a measured inductance of 2.65 millihenrys, was connected in series with a coupling coil of 0.77 millihenry and a variable mica and air condenser for tuning. As the observations were confined entirely to wave lengths over ten kilometers, the tuning capacity was large, ranging from 0.013 microfarad for Nauen to 0.045 microfarad for the Lafayette station at Bordeaux. Preliminary tests indicated that a small ratio of inductance to capacity gave marked freedom from antenna effects, and the polar curve was found to be very symmetrical, as will be seen from Figure 3, taken on the Marion station, some 150 kilometers (93 miles) to the south.

* Diameter of number 22 wire = 0.025 inch = 0.063 cm.

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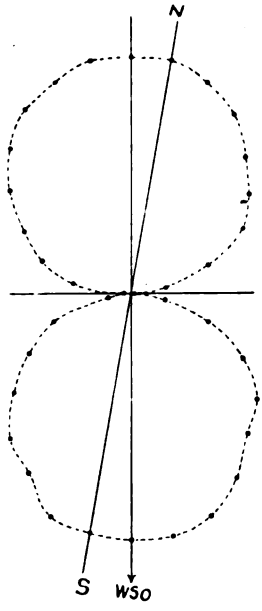

FIGURE 3

The coil was mounted on a wooden platform, with the lower wires of the loop 180 centimeters (5.9 feet) above the ground, and leads were taken into a wooden hut nearby, which housed a receiving circuit with four stages of radio and two of audio frequency amplification, an external heterodyne, and a shielded local source of oscillations for intensity measurements. A small open antenna was also erected for unilateral working, in combination with the loop. Figure 4 shows the coil and hut, looking north along the beach, while Figure 5 shows the interior of the receiving hut.

Bearings were taken to the nearest degree, and sometimes to the nearest half degree. Over a thousand determinations were made, principally on Nauen and Bordeaux, and in no single instance was there any uncertainty as to the null point, such as has been reported by other observers. Ocassionally severe static would bury the signal for five or ten degrees on either side of the null point, and on a few occasions the unsymmetrical distribution of the static (stronger on one side of the null point than on the other) made the bearing uncertain by as much as seven or eight degrees. Observations made under such conditions are not included in the results reported in this paper.

No sudden changes in direction were observed, the bearings

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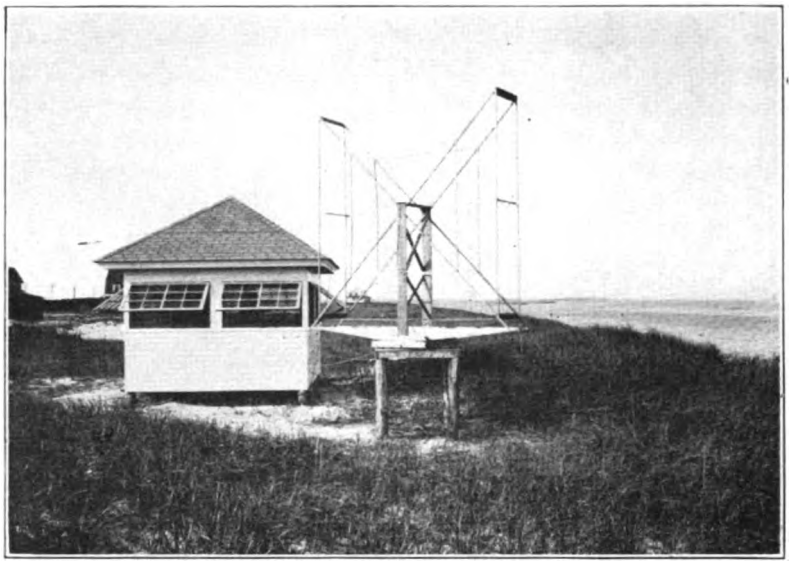

FIGURE 4

simply drifting slowly from side to side of the mean bearing for the period. This is well shown by a portion of the Seabrook station log, reproduced below, of August 15, 1921.

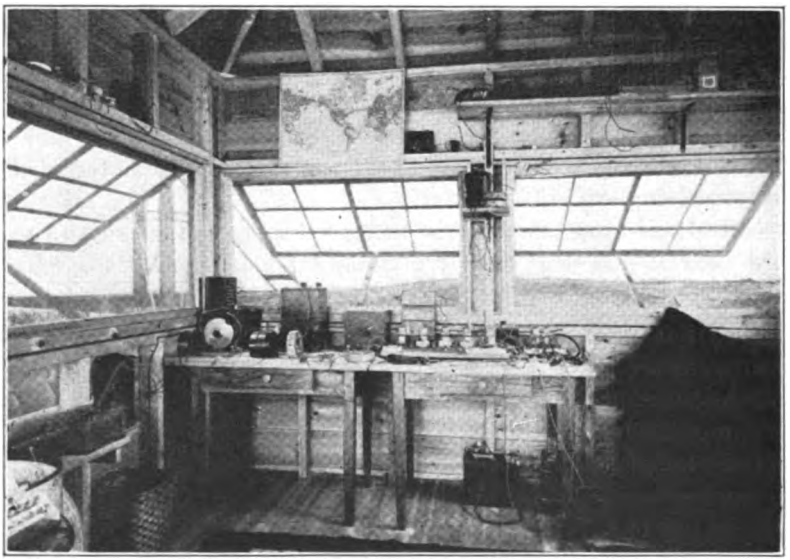

FIGURE 5

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Time 75th Mer.	Station	Bearing	Intensity Volts per Meter $\times 10^{-5}$
10.03 A.M.	Nauen	N49E	1.8
10.05 A.M.	"	48	
10.15 A.M.	"	48	
10.19 A.M.	"	50	
10.40 A.M.	"	52	
10.43 A.M.	"	51	
10.45 A.M.	"	50	
10.49 A.M.	"	50	
10.52 A.M.	"	51	
10.54 A.M.	"	50	
10.55 A.M.	"	50	
10.57 A.M.	"	50	
10.59 A.M.	"	50	
11.01 A.M.	"	50	
11.07 A.M.	"	50	
11.10 A.M.	"	50	
11.14 A.M.	"	51	
11.17 A.M.	"	51	
11.18 A.M.	"	52	
11.22 A.M.	"	51	
11.30 A.M.	"	50	
11.33 A.M.	"	50	
11.42 A.M.	"	50	
11.44 A.M.	"	51	
11.46 A.M.	"	51	1.3
12.40 P.M.	"	50	
12.44 P.M.	"	51	
12.48 P.M.	"	50	
12.52 P.M.	"	50	
12.58 P.M.	"	50	
1.03 P.M.	"	50	
1.06 P.M.	"	50	
1.09 P.M.	"	51	
1.12 P.M.	"	50	
1.19 P.M.	"	50	
1.21 P.M.	"	51	
1.26 P.M.	"	51	
1.35 P.M.	"	51	
1.43 P.M.	"	51	
1.48 P.M.	"	52	
1.52 P.M.	"	52	
1.57 P.M.	"	52	1.2
2.09 P.M.	Bordeaux	N65E	4.7
2.13 P.M.	"	65	
2.15 P.M.	"	62	
2.19 P.M.	"	60	

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Further, no marked changes in bearing occurred at either sunset or sunrise, as will be apparent by inspection of a portion of the Seabrook station log of August 15, 1921, covering the sunset period.

Time 75th Mer.	Station	Bearing	Intensity Volts per Meter $\times 10^{-5}$
5.12 P.M.	Nauen	N52E	0.9
5.29 P.M.	"	52	
5.31 P.M.	"	52	
5.34 P.M.	"	52	
6.17 P.M.	"	52	
6.22 P.M.	"	52	
6.25 P.M.	"	52	
6.31 P.M.	"	52	1.3
6.35 P.M.	"	50	
6.39 P.M.	"	51	
6.54 P.M.	"	50	
6.57 P.M.	"	50	
7.02 P.M.	"	50	
7.05 P.M.	"	50	
7.08 P.M.	"	52	
7.10 P.M.	"	53	
7.12 P.M.	"	53	
7.18 P.M.	"	50	
7.26 P.M.	"	50	
7.28 P.M.	"	51	
7.29 P.M.	"	50	
7.31 P.M.	"	51	
7.36 P.M.	"	52	
7.43 P.M.	"	49	
7.45 P.M.	"	49	
7.49 P.M.	"	51	
8.00 P.M.	"	48	1.9
8.06 P.M.	"	47	
8.09 P.M.	"	51	
8.11 P.M.	"	50	
8.13 P.M.	"	52	
8.16 P.M.	"	51	
8.19 P.M.	"	51	
8.21 P.M.	"	53	
8.24 P.M.	"	52	
8.27 P.M.	"	49	
8.29 P.M.	"	50	
8.32 P.M.	"	50	2.2

And from a portion of the Seabrook log of August 26, 1921, covering the sunrise period.

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Time 75th Mer.	Station	Bearing	Intensity Volts per Meter $\times 10^{-5}$
12.03 A.M.	Bordeaux	N77.5E	15.
12.18 A.M.	Nauen	N57E	
12.21 A.M.	San Diego	W5N	
12.36 A.M.	Nauen	N57E	3.1
1.54 A.M.	San Diego	W8N	
2.03 A.M.	"	W7N	
3.33 A.M.	"	W10N	
4.28 A.M.	"	W10N	
4.40 A.M.	"	W9N	
4.45 A.M.	"	W7N	
4.50 A.M.	"	W7N	
4.53 A.M.	Nauen	N55E	
5.03 A.M.	Bordeaux	N70E	6.0
5.07 A.M.	San Diego	W5N	
5.11 A.M.	"	W5N	
5.15 A.M.	"	W7N	
5.18 A.M.	"	W6N	
5.38 A.M.	"	W7N	
5.50 A.M.	"	W7N	
5.57 A.M.	"	W6N	
6.01 A.M.	Nauen	N55E	
6.14 A.M.	"	N55E	
7.51 A.M.	Bordeaux	N70E	5.2

Owing to the mass of observations on Nauen and Bordeaux, which would be confusing if individually plotted, each day was divided into four periods of six hours each; midnight to six, six to noon, noon to six and six to midnight, and the observations taken in each such period were averaged and plotted as a point on the curve for the month.

In Figure 6 the upper two curves are for Nauen and Bordeaux apparent bearings, the heavy datum lines representing the true or great circle bearing of these two stations. All of the deviations are to the East of the true bearing, and it will be noted that they are in general small during the first part of the month, but increase markedly during the last week in August. Also, altho Nauen and Bordeaux deviations vary together, the maxima and minima do not always fall in the same six-hour period.

Concurrently with these bearings, a long series of intensity measurements was made, and the results of these measurements are plotted at the bottom of Figure 6. It will be seen that the signals rose appreciably in intensity during the last week in

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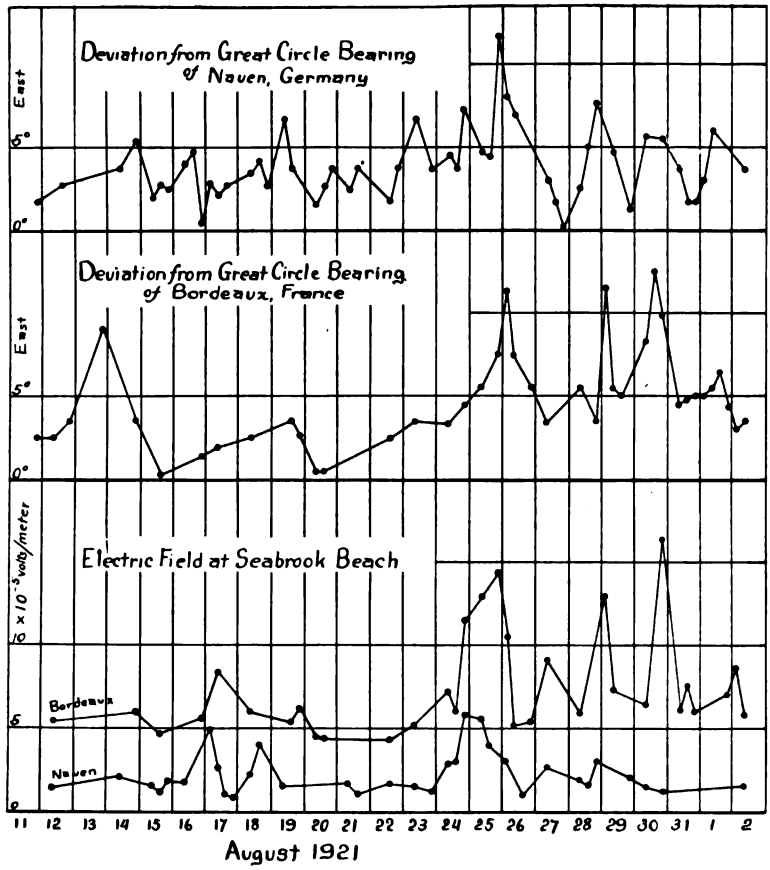

FIGURE 6

August, coincidently with the periods of maximum deviation from true bearing. These intensity measurements are given in volts per meter at Seabrook, and were taken by a method devised by the writer, which avoids the complications and uncertainties of the Vallauri method, and gives readings directly in terms of the electromotive force produced in the receiving circuit. The arrangement employed is shown in Figure 7.

A tube-driven wave-meter circuit C1 L1 (L1 being a toroidal air core inductance) is coupled by way of a secondary coil L2 with a non-inductive resistance network R1, R2, R3. R1 and R3 are small resistances, usually about half an ohm each, while R2 is variable between sufficiently wide limits to give any desired fall of potential across R3. A hot wire meter, HWM, giving full scale deflection on about 0.07 ampere, with a reading microscope focused

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on the pointer, can be inserted in either the secondary circuit L2, R1, or, by throwing the switch SW to the left, into a direct current circuit B, MA, R4, the current in this circuit being read by the milliammeter MA. When R4 is so adjusted that the meter HWM shows no change of deflection on throwing SW, it is obvious that the oscillating current flowing thru R1 is equal to the current read by MA. With an oscillating current of the

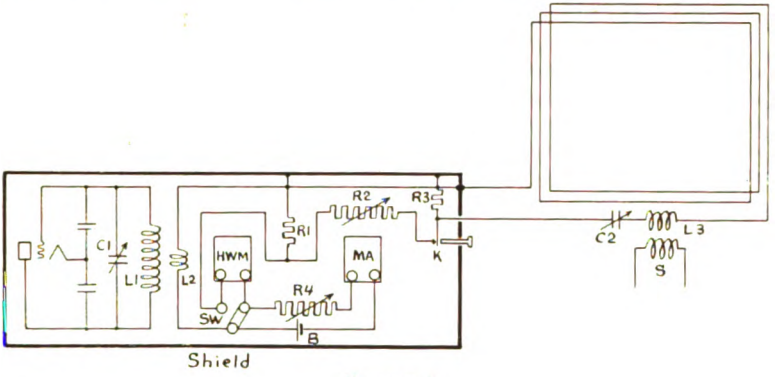

FIGURE 7

order of 0.01 ampere, this arrangement is sensitive enough to check the current to within about 1 percent; an ample precision for any aural comparison method. With the distant station sending, the oscillating circuit C1, L1 is tuned exactly to the same frequency, as checked by the beat note in the detector circuit. Then, by tapping the key K so that short signals from the shielded local circuit may be intercalated with the signals from the distant station, and varying R2 until the intensity of the two signals became observably equal, the electromotive force across R3 is equal to that produced in the loop by the distant station, and may be found by a simple calculation from the known constants of the resistance network. Also, from the electromotive force produced in the circuit, the electric force in the wave-front is easily calculated from the wave length, number of turns and size of the coil aerial.

On the night of September 1-2, 1921, a strong aurora developed at about 9.30 P.M., and persisted thruout the night and even after dawn. During the greater part of this time, the Bordeaux station was sending, and the writer made a series of bearing and intensity measurements to determine whether the aurora had any effect upon radio waves. The results of this measurement are set forth in the table below.

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OBSERVATIONS DURING THE AURORA OF SEPTEMBER 1-2, 1921

Time 75°M	Bearing	Deviation	Intensity $\times 10^{-5}$	Notes
P.M.				
9.50				Strong auroral arc, center N5E, 115° wide. Static S70W.
10.15	N67E	4.5E		Bordeaux sending.
10.30	67	4.5		Aurora increasing.
10.40	67	4.5		
10.44	66	3.5		
10.48	67	4.5		
10.55	67	4.5		Second arc above original one.
11.00	66	3.5	7.6	
11.09				Ends of lower arc developing hooks.
11.10	67	4.5		
11.14	68	5.5		
11.20	66	3.5		Upper arc develops hook at E.
11.26	66	3.5		Upper arc changes to vertical brush. Aurora fading.
11.32	67	4.5		
11.36	67.5	5.0		
11.40	67	4.5		Static S70W.
11.47	67	4.5		Aurora wing-like, center N.
11.54	66	3.5		Aurora fading.
11.58	67	4.5	6.6	
A.M.				
12.05	67	4.5	10.2	Aurora strong, and now a simple arc.
12.08	67	4.5		
12.13	67	4.5		Aurora fading slightly.
12.20	66	3.5		
12.25				LY stops sending. At 1.20 aurora began to flicker, culminating at 1.30 in a magnificent flame-like effect which covered the entire northern half of hemisphere.
1.53	67	4.5	6.0	
1.57	65	2.5		
2.03	65	2.5	4.1	
2.09	64	1.5		
2.13	65	2.5		Static S65W. Aurora fading slightly. Static S80W.
2.17	65	2.5		
2.21	65	2.5		
2.26	65	2.5		Aurora fading.
2.30	65	2.5		Aurora increasing.
2.34	65	2.5		Aurora fading.
2.37	65	2.5		Aurora strong in NW.
2.41	65	2.5		Aurora increasing.
2.44	65	2.5		Aurora fading slightly.
2.47	65	2.5		Aurora weak.
2.51	66	3.5		Only a few patches of aurora left.
2.54	66	3.5		
2.58	65	2.5		Static S60W.
3.01	66	3.5	7.2	Aurora increasing.
3.05	66	3.5		Aurora faint.
8.40	66	3.5	5.8	

The aurora seemed to be without effect upon either the bearing or intensity of Bordeaux, and even that eratic element, static, came in from about its normal bearing, and with its usual intensity, thruout the display.

In addition to the many measurements made upon Nauen

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and Bordeaux, a few bearings were taken from time to time on stations in the United States, and these are given in the table below.

Date	75th Mer. Time	Station	Bearing	Deviation
Aug. 12	9.00 A.M.	New Brunswick	S56W	5.7W
13	10.15 A.M.	Annapolis	S42W	7.0S
13	10.30 A.M.	New Brunswick	S48W	2.3S
13	10.05 P.M.	Annapolis	S52W	3.0W
13	10.12 P.M.	Glace Bay	N58E	5.3N
14	11.50 A.M.	Marion	S2.5E	0.9E
14	12.10 P.M.	Annapolis	S42W	7.0S
14	12.25 P.M.	New Brunswick	S53W	2.7W
15	9.05 P.M.	Glace Bay	N60E	3.3N
16	11.05 A.M.	Marion	S5E	3.4E
17	3.22 P.M.	New Brunswick	S52.5W	2.2W
19	4.51 P.M.	Marion	S10E	8.4E
23	10.00 P.M.	Annapolis	S57.5W	8.5W
24	9.07 A.M.	Marion	S4.7E	3.1E
24	12.03 P.M.	Annapolis	S53W	4.0W
24	12.07 P.M.	"	S53W	4.0W
25	10.03 P.M.	"	S46W	3.0S
25	11.37 P.M.	San Diego	W7N	9.5N
25	11.58 P.M.	"	W10N	12.5N
26	12.21 A.M.	"	W 5N	7.5N
26	1.54 A.M.	"	W 8N	10.5N
26	2.03 A.M.	"	W 7N	9.5N
26	3.33 A.M.	"	W10N	12.5N
26	4.28 A.M.	"	W10N	12.5N
26	4.40 A.M.	"	W 9N	11.5N
26	4.45 A.M.	"	W 7N	9.5N
26	4.50 A.M.	"	W 7N	9.5N
26	5.07 A.M.	"	W 5N	7.5N
26	5.11 A.M.	"	W 5N	7.5N
26	5.15 A.M.	"	W 7N	9.5N
26	5.18 A.M.	"	W 6N	8.5N
26	5.38 A.M.	"	W 7N	9.5N
26	5.50 A.M.	"	W 7N	9.5N
26	5.57 A.M.	"	W 6N	8.5N
26	12.04 P.M.	Annapolis	S52W	3.0W
27	10.44 P.M.	San Diego	W15N	17.5N
27	11.28 P.M.	"	W13N	15.5N
27	11.58 P.M.	"	W12N	14.5N
28	8.42 A.M.	"	W12N	14.5N
28	12.11 P.M.	Annapolis	S55W	6.0W
29	10.45 A.M.	Tuckerton	S40W	1.7S
29	1.03 P.M.	Annapolis	S52W	3.0W
29	10.03 P.M.	"	S47W	2.0S
30	12.04 P.M.	"	S52W	3.0W
31	12.01 P.M.	"	S52.5W	3.5W
Sept. 1	12.01 P.M.	"	S51.5W	2.5W

With the exception of Glace Bay, all of these stations were received entirely overland, and it will be noted that, with the exception of San Diego, the deviations are small and of the same order as those observed for the European stations.

The averages for the entire month, and of both night and day observations, are given in the table below.

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Station	True Bearing	Deviation
Annapolis	S49W	0.5W
Tuckerton	S41.7W	1.7S
New Brunswick	S50.3W	2.1W
Nauen	N48.3E	3.8E
Marion	S1.6E	4.0E
Bordeaux	N62.5E	4.2E
Glace Bay	N63.3E	4.3N
San Diego	W2.5S	10.6N

It is to be regretted that these observations did not cover a much greater period, and it is to be hoped that before long someone will undertake continuous observations of this character. It is only thru the accumulation of such data that we can hope to correlate these variations in direction and intensity with meteorological and other terrestrial elements, and in this way arrive at an understanding of their causes. Heaviside Layer hypotheses are of little value unless supported by a firm founda tion of data, and as Lord Kelvin said:

> "When you can measure what you are speaking about and express it in numbers, you know something about it, and when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind. It may be the beginning of knowledge, but you have scarcely in your thought advanced to the stage of a science."

SUMMARY: The deviations of radio goniometric readings from the true bearing of distant and nearby stations were measured at a suitable location with a coil antenna and receiver. In addition to errors due to physical obstructions in the path of the incoming wave, errors varying with the time of day were measured. Radio goniometric measurements were also made dnring an intense aurera. The intensity of the field of the incoming signals was also measured by means of a resistance network, and the necessary apparatus is described.

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THE RECORDING OF HIGH SPEED SIGNALS IN RADIO TELEGRAPHY*

By

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Introduction

In this paper it is proposed to deal with the development and operation of a practical system for the handling of radio telegraphic traffic at high speed, particularly in trans-oceanic communication. By high speed working we refer to operation at speeds greater than those customarily employed for telephonic reception, that is 20 to 25 words per minute by average good operators.

With the continually increasing expensiveness of equipment, and the tendency towards increase of transmitting power (so as to insure reliable communication at all times), it has become apparent that the profitable operation of a long distance radio system depends greatly upon working at a rate of speed in excess of that obtainable by hand. Most of the high power radio transmitters of today are equipped with relay systems capable of sending as high as 100 words per minute, and there is no particular reason why, if necessary, powerful vacuum tube amplifiers could not be built to take the place of relays and be worked at considerably greater speed. The limitation of working speed is practically confined to the receiving side of the radio system, so that it is obvious that increased speed possibilities must be obtained entirely by the development of receiving apparatus.

In order to understand the conditions under which high speed recording apparatus must work, it will be well to describe briefly the manner in which communication is carried on over the trans-Atlantic circuits of the Radio Corporation. Figure 1 illustrates the method of duplex working. It will be noted that the operation is from New York City, while the transmitting and receiv-

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ing stations are placed at some suitable distant point; and it is intended to concentrate most of the Atlantic Coast transmitters in a central plant at Port Jefferson, Long Island, while most of the receivers are concentrated at Riverhead (about 18 miles (29 km.) from Port Jefferson). All control of the various trans-

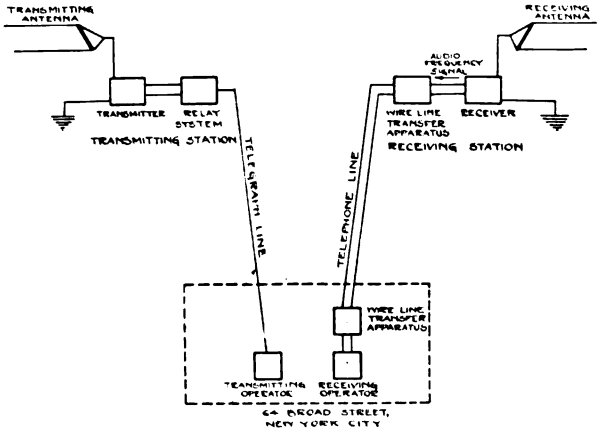

FIGURE 1—Radio Corporation of America: Method of Centralized Operation

mitters and receivers is from New York City, the sending operator controlling a transmitter via telegraph line and the receiving operator having the received audio frequency signal brought to him via telephone line. The transmitting and receiving operators are located close to one another (at a common table), so as to facilitate duplex operation. The receiving operator can thus instantly communicate with the distant transmitter, if desired, in order to control the speed of transmission, or stop the transmission in case of trouble. The operators themselves handle no apparatus whatsoever; the receiving and transmitting apparatus is handled by engineers at the respective stations, and such apparatus as is necessary for wire line transfer at Broad Street is placed in a room separate from the operating room and maintained by men of suitable qualifications.

REQUIREMENTS OF HIGH SPEED RECORDING APPARATUS

The foregoing operating arrangement, as well as certain service standards, imposes a series of requirements upon high speed recording apparatus which are given below:

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1. Minimum delay between the time of recording and the time of transcribing the signals. This is of importance in

(a) Successful duplex operation: In case of trouble (for example, bad relay adjustment in the transmitting station) or for other reasons, it may become necessary to stop the distant transmitter. If the record is not immediately perceptible, a considerable quantity of traffic might be sent which was not properly recorded, and which would then have to be repeated, with consequent loss of circuit time and delay in delivery.

(b) Prompt delivery of messages to the customer

(c) Observation of the effect of adjustment of the receiving or transmitting apparatus. It is essential that a minimum delay shall occur between the time a change of adjustment is made and the time the effect of the change is perceived.

2. The cost of recording must be as low as possible—not over a few hundredths of a cent per word. This is important since a large class of reduced rate traffic, such as press matter, deferred delivery messages, and the like, is handled at high speed. Furthermore, the future operating of short distance radio circuits with low rates must be taken into consideration, since the equipment designed for long distance working should be standardized for all classes of service if possible. Therefore the initial cost of the equipment must be low, as well as the operating and maintenance charges.

3. The recording equipment must be as simple and rugged as possible, and require no continuous attention; since it must be located near the receiving operators and handled by the telegraph supervisors, who generally do not have extensive technical or engineering qualifications. The parts of which the equipment is constructed should be capable of easy repair in case of breakage, as far as possible, by the men and facilities available in the operating rooms, and spare parts should be capable of easy installation by such men. This is more important when recording equipment is furnished to stations other than those located in New York City (such as those in Hawaii or on the Pacific Coast), to which it would be manifestly very expensive to send expert repair men.

4. A record capable of preservation is highly desirable, so as to check up errors, and for use as a means of traffic study and general service improvement.

5. The tone signal which is sent over the telephone line from the receiving set may be anywhere between 500 and 1,500 cycles. (Altho the lines will transmit, theoretically, frequencies up to

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2,200 cycles, it has been found in practice that better transmission is secured by keeping signals below about 1,500 cycles). The recording equipment must be capable of accepting any given frequency in this range, and allow for a considerable fluctuation above or below this frequency. It has been found in practice that at present frequency fluctuations of several hundred cycles must be taken into account with some European transmitters; tho improvements in this respect no doubt will be made. A fluctuation of signal intensity of the order of perhaps 2 to 1 must be taken into account, due to accidental changes in line conditions, amplifier adjustments, or during tuning of the receiving equipment at the distant station.

6. Speed Limitations: Present practice in long distance high speed working is on the basis of from 40 to 50 words (200 to 250 letters) per minute, and at times higher speeds, up to 80 words per minute, have been commercially handled. The limitation lies in relay trouble at the transmitting end and strays at the receiving end of the circuit. It is probable that working at 100 words per minute will eventually become the rule tho not for a number of years. Hence, a recording system should be able to handle easily speeds up to 80 words per minute, and be so designed that extension to higher speeds (say, up to 200 words per minute) can be accomplished by simple modifications, for use on short-distance circuits. It is interesting to note, in this connection, that European short-distance radio circuits (for example, London-Paris, and London-Berlin), are understood to be operating regularly at 60 words per minute, and operation up to 100 words per minute has been carried on at times.

7. The perception of the recorded signal by the operator should be made as easy as possible. The operator has not the time to study the record, and an easily perceived record at lower speeds is preferable to one at a higher speed which requires study on his part. For example, in graphic recorders the contrast between recorded signal and background should be great, the letters clean-cut, so that the operator perceives them instantly, and static eliminated from the record to the maximum extent consistent with accuracy. In acoustic recorders (such as the phonograph or the telegraphone) the signal heard by the transcribing operator must be clear and loud, free from musical static and with firmly-formed dots and dashes. It is difficult to overestimate the importance of this requirement; it has a great influence on commercially successful operation, for the speed at

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which operators will handle traffic depends considerably on the clearness of the signals with which they deal.

8. The effort necessary, on the part of the operator, to distinguish the signal from such record as may be produced by static, in the ideal case, should be equal to or less than that necessary for aural reception with head telephones.

9. Continuous operation of the recording equipment is essential. In the case of acoustic recorders, where it takes some time to place a new record on the machine, two overlapping recorders must be used, one being started just before the record is removed from the other. But the installation of two machines is uneconomical and continuous operation should be provided for, in the ideal recorder, in a single machine.

Available Types of Recording Equipment

When the Research Department started on the developmen of a commercially practical and modern high speed reception system there were available a number of different types of recording apparatus, which were taken under consideration. These may be divided into two general classes, namely acoustic and graphic recorders. We will consider these below:

(A) Acoustic Recorders

This type of recorder is connected to the radio receiving set in place of the operator's telephones; and generally some audio frequency amplification ahead of the recorder is required so as to overcome the losses occurring in the recording and reproducing process. The particular advantage in acoustic recording methods is that the experience of the operators in reading signals thru strays by ear is utilized. When recording high speed signals, the tone of the received signal is raised to a high pitch at the receiving set by appropriate adjustment, and the machine run at its maximum speed; for reproducing, the speed of the machine is lowered and the tone of the reproduced signal is, of course, lower in proportion. For example, in phonographic recorders it is customary to reproduce with the record rotating at about 100 revolutions per minute at a note of, say 800 cycles, and a speed of about 15 words per minute. Then when recording 80 words per minute, the record as rotated at 400 revolutions per minute, and a recording tone of 3,200 cycles must be used.

A typical acoustic recording and transcribing installation comprises two recording machines (so as to afford continuous operation and numerous reproducing machines. The records

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are distributed from the recorders to operators at the various reproducers for transcription.

Two types of acoustic recorders have been used to some extent in radio practice. The first of these is the well-known Poulsen telegraphone, in which a steel wire runs at high speed past a pair of electromagnets thru which the audio frequency current to be recorded flows. The record is in the form of magnetic charges which remain fixed on the wire. In other types, which were not available in this country, the record is made on a disk, or on a cylinder, similar in nature to the records used in disk or cylinder phonographs. It is possible to erase the record by a suitable uniform magnetisation of the steel. Figure 2 shows the type of wire telegraphone which has been used radio reception.

FIGURE 2—Steel Wire Telegraphone

The second type of recorder is the phonograph; this has been employed in the form of an ordinary office dictating machine (in this country the "Dictaphone" and the "Ediphone" have both given good service) with cylindrical wax records. The signal from the receiving set is brought to a special telephone receiver (hav-

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ing a highly damped diafram so as to reduce the musicality of the record due to strays) after passing thru an amplifier giving several hundred times voltage amplification. This receiver is mounted directly on the intake of the recording head. In Figure 3, the method of recording and, in Figure 4, the method of transcribing are shown.

FIGURE 3—Phonographic High Speed Recording

Both varieties of acoustic recorders have a number of inherent defects and disadvantages. These are considered under the following headings:

(1) DELAY IN OBTAINING TRANSCRIBED MESSAGES

In the steel wire telegraphone, as ordinarily constructed for office work, a very large amount of wire is supplied; so that a period of approximately half an hour elapses before the recorded

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signals are available for transcription. This length of time is quite prohibitive from an operating standpoint.

In the phonograph, from four to six minutes elapse between the time of recording and transcription, which is still considered as unsatisfactory. In both these cases the time is objectionable because of the delay in the delivery of messages and the difficulty of adequate supervision of the quality of the recorded signal.

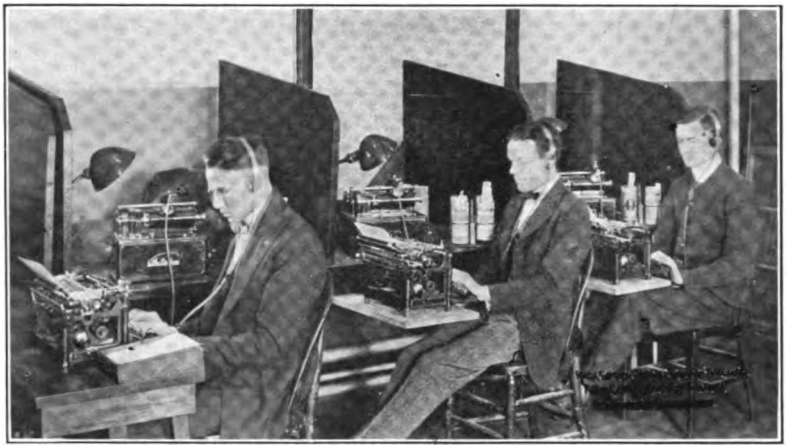

FIGURE 4—Transcribing Phonographic High Speed Records

(2) COST

An acoustic recording installation requires two recording machines and from four to six transcribing machines; in operation, one man is required to attend the recorders (put on and take off records), one man to erase previous records (operating shaving machine in the case of phonographs or erasing machine with telegraphones) and distribute records to the transcribing operators, and four or six transcribers. Thus the installation and operating cost of this type of system is extremely high. As will be shown later, cost is reduced to a minimum in the present type of recording system developed by the Research Department.

(3) LACK OF PERMANENT RECORD

This is an important disadvantage in acoustic recording systems. It is highly desirable to preserve a record of the received messages, so as to place responsibility for errors, and as a means of studying the quality of received signals. If this were done with acoustic recording systems, the operating cost would be prohibitive, because of the expense of the record blanks.

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Thus, it is necessary to erase the recorded messages (by shaving in the case of the wax phonograph cylinder, or magnetic erasure on the telegraphone wire); and this is generally done immediately after transcribing, so that operation may be carried on with a minimum quantity of blanks.

(4) Mechanical Disadvantages:

In the telegraphone, the steel wire running at high speed sometimes breaks. When this happens it is possible that it may become rather badly snarled and it may be impossible to recover a considerable quantity of the tangled wire in order to transcribe it, while the repairing of the broken wire necessitates rather expert attention.

In the phonographic office dictating machines considerable ingenuity has been expended to make them "fool-proof;" but they still require careful and continuous attention in order to make them give the best records.

Both the telegraphone and phonographs require an expert repair man in case of trouble, contain a multitude of parts, and should have a periodic overhauling. In the case of control-station operation in New York City this is not so serious, but it is undesirable for more isolated stations.

(5) Limitations of Usefulness in Central Station Operation with Wire Line Transfer

In the method of operation shown in Figure 1, it has been mentioned that it is advisable to remain below 1,500 cycles for the pitch of the audio frequency signal transmitted over the telephone line. This imposes a serious speed limitation on acoustic recording systems because of the necessity of lowering the pitch for transcribing. Assuming transcription to occur at 800 cycles and 20 words per minute, this system would be limited at best to a speed of about 40 words per minute.

(B) Graphic Recorders

Two main classes of graphic recorders may be taken under consideration:

(1) The photographic type, in which the signals are recorded on photographic paper.

(2) The stylographic type, in which the signals are written down with ink on ordinary paper, either in the form of a wavy line or as dots and dashes.

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(1) Photographic Recorders

In this class, there were available the Einthoven galvanometer type and the Hoxie recorder of the General Electric Company. The former had been used to some extent by European radio companies, and the latter by the United States Navy, as well as on commercial work in Radio Corporation stations. Since the Hoxie apparatus was immediately available and obviously superior to the Einthoven galvanometer in type of record, mechanical construction, and so on, our attention was restricted to it.

The Hoxie recorder has already been discussed before this Institute and a description may therefore be omitted. This instrument has a number of advantages as a radio recorder; it delivers a fairly faithful record of the received signals and strays, has extraordinarily high speed capabilities (far in excess of what is actually required) and will work directly on a current of an order of magnitude the same as that used for good telephonic signals (15 microamperes). Thus it may be used directly in place of the operator's telephones, requiring no extra amplification, and forms a valuable instrument for purposes of research or oscillographic investigation where records over long periods of time (one or more hours) are desired, and the expense of the photographic tape is not objectionable.

(2) Stylographic Recorders

This class includes the Morse inker, and the siphon recorder. Both of these have been long used in telegraph and cable practice, and meet the important commercial requirements of instantaneous visibility of the recorded signal, cheapness, permanence of record, and continuous operation. Such other requirements as were not fulfilled by existing types of this apparatus (speed capability and mechanical simplicity) could obviously be met by further development; and, accordingly, we concluded that our attention should be centered along these lines.

(a) Morse Inker (Wheatstone Automatic Recorder)

Essentially, the Morse inker may be considered as a telegraph sounder (or polarized relay) carrying a small sharp-edged wheel on the end of the sounder armature, the edge of the wheel being kept moistened with rather thick ink, and with paper tape moving under the wheel. When the sounder magnets are energized by direct current the armature comes down and the inked wheel makes a dot or dash on the paper, depending upon the length

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of time the current remains on. The current required to operate a typical instrument is about 50 milliamperes, the resistance of the magnet windings being of the order of 1,000 ohms (an energy requirement of about 2.5 watts). It will be recalled that the Morse inker and coherer formed the first type of radio receiving system ever used, and in Europe, to-day, the Morse inker is again being employed in high speed radio reception.

Two methods of connecting the inker to the receiving set have been used. In one, the audio frequency signal is amplified to an extent such that energy of the required order of magnitude may be furnished; but this is very cumbersome (since for this comparatively large amount of energy, power tubes and amplifiers using several hundred volts of plate battery are necessary) and really unnecessary in view of the type of record; so that it is generally more customary to operate the inker thru a relay. The simplest method is to place the magnet winding of a sufficiently sensitive telegraph relay in the plate circuit of a detector tube, so that when the direct plate current of the tube varies with the audio or radio frequency voltages impressed on its grid, the relay armature is operated, and the inker may be worked from the relay armature contacts. More complex, but also more reliable methods than this have been developed, and some of these are described in publications given under "Bibliography."

The Morse inker has the disadvantage that the record which it makes can only be a dot or dash. Thus, if strays in the form of individual clicks are present, in sufficient strength, a dot will be printed for each stray click. If the strays are more or less continuous (in the form of rapidly successive clicks or crashes) a continuous dash will be made. Therefore, the reading of a message thru static has been found by experiment to be much more difficult on Morse inker than on siphon recorder tape (in which the record is in the form of a wavy line). When the inker is operated thru a relay, the latter is tripped or held closed by the strays so that the inker is falsely operated; the effects of strays in this arrangement are even worse than if the inker is merely operated thru an amplifier.

It was judged most advisable, therefore, to work along the lines of the siphon type of record and to develop an instrument which, with a moderate amount of amplification, would record directly the rectified audio frequency current of the operator's signal. The requirements determined upon were that the instrument should work on a rectified current of a few milliamperes, and be capable of recording readily at the rate of 100 words per

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minute, with the capability of eventual extension to higher speeds by small alterations of the parts.

(b) Siphon Recorder

An examination of the existing types of siphon recorders was then made. All the commercial forms that we were aware of consisted essentially of the parts shown in Figure 5. In this instru-

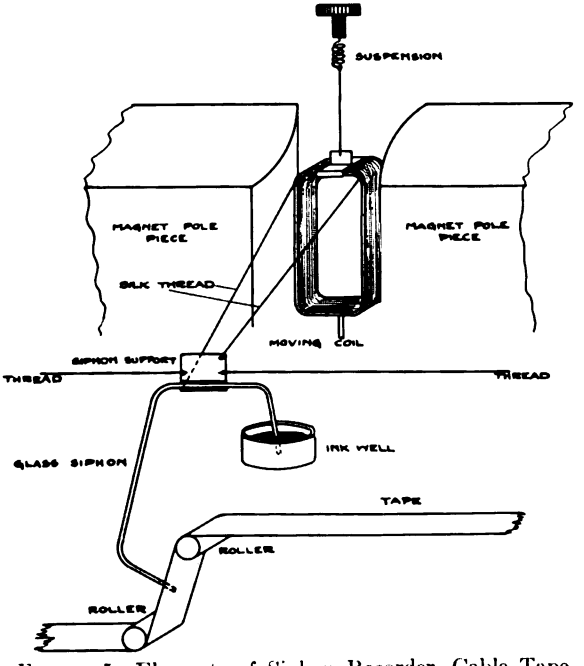

Figure 5—Elements of Siphon Recorder, Cable Tape

ment a galvanometer coil is placed between the poles of a powerful magnet so that when the current to be recorded passes thru the coil, it turns on its vertical axis; threads are attached to the upper corners of the coil form, which pull a small fiber piece called the "siphon support" as the coil rotates, so that the glass siphon travels back and forth over the moving tape. The siphon consists of a fine glass tube having a hole of the order of 0.01 inch (0.25 mm.), bent as shown in the figure, and secured to the support by wax. An ink well is placed above the tape and the end of the siphon allowed to dip into it; since the end of the siphon on the tape is lower than that in the ink well, the ink is caused to flow thru continuously. Adjustments for the height and angle of the tape,

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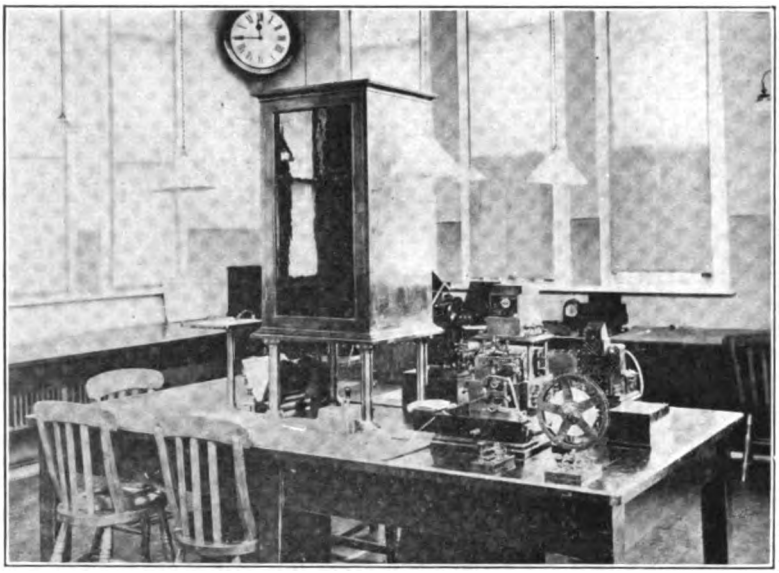

FIGURE 6—Cable Type of Siphon Recorder Installation

and for the tension and position of the various threads and suspensions are also provided. These will be best seen in Figures 6 and 7, which are photographs of the type of siphon recorder used in cable stations.

This type of recorder will deliver good signals on a few hundred microamperes; but because of the cumbersomeness of the moving parts, its speed is limited to less than 50 words per minute.

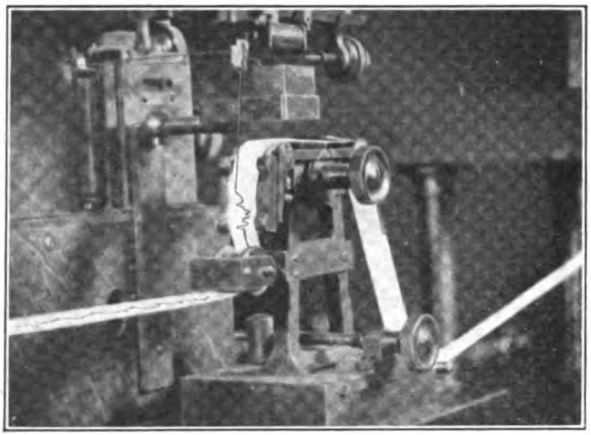

FIGURE 7—Cable Type of Siphon Recorder, Pen, and Tape Mechanisms

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Similar instruments, called "undulators," may be obtained which will record up to 100 words per minute, but which require currents of the order of 50 milliamperes, and would therefore have to be operated thru a relay as in the case of the Morse inker. In either case, the recorded signals at the higher speeds are badly rounded (instead of rectangular); a series of dashes appears as a set of "V's" following each other. Figure 8 indicates the type of record given by the cable type of siphon recorder on successive dashes at the comparatively moderate speed of 60 words per minute.

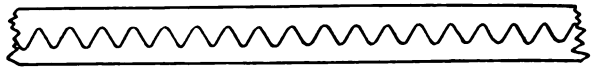

FIGURE 8—Record of Dashes at 60 Words per Minute on Cable Type of Siphon Recorder

In addition to the speed limitations, and poor type of record, the mechanical features of the siphon recorders which were available in the open market rendered them quite unsatisfactory for radio use. For example, the long glass siphon requires skill to make and mount, and in case of breakage or clogging it takes considerable time to put on a new one; while in connection with the various adjustments and general construction of parts it was felt that improvements could be made which would render the instrument more simple, convenient, and better adapted to meet the rather rough usage such a device would receive in radio stations.

Accordingly, it was next decided to undertake the development of a mechanical form of recorder having the desired characteristics. The form which was developed was a distinct departure from the old cable type, and became known later on as the "Ink Recorder," by which title we shall refer to it hereafter.

MECHANICAL DEVELOPMENT OF INK RECORDER

The original idea and the mechanical development of this recorder are due to Mr. Edward Blakeney; and the design of the commercial apparatus to Mr. Blakeney and Mr. Samuel C. Miller, of the Research Department.

Without going into the various development models, with their usual record of small detailed changes, it will be best to describe only the final commercial type, since the essential parts remained practically the same thru the development.

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The essential parts of the recording system are indicated in Figure 9. A small circular coil is placed in the radial field produced by a powerful solenoid type of electromagnet; rising from the coil frame a link engages the pen arm. The latter is supported at one end by a thin, wide steel spring (called the fulcrum spring) and carries at its outer end a short piece of metal tubing, about half an inch (1.27 cm.) long, called the pen. This pen takes ink from a device called the "ink feed" at one end and writes on the paper tape at the other. The coil frame, pen arm, and link are made of thin aluminum sheet; the pen is a small size of brass tubing.

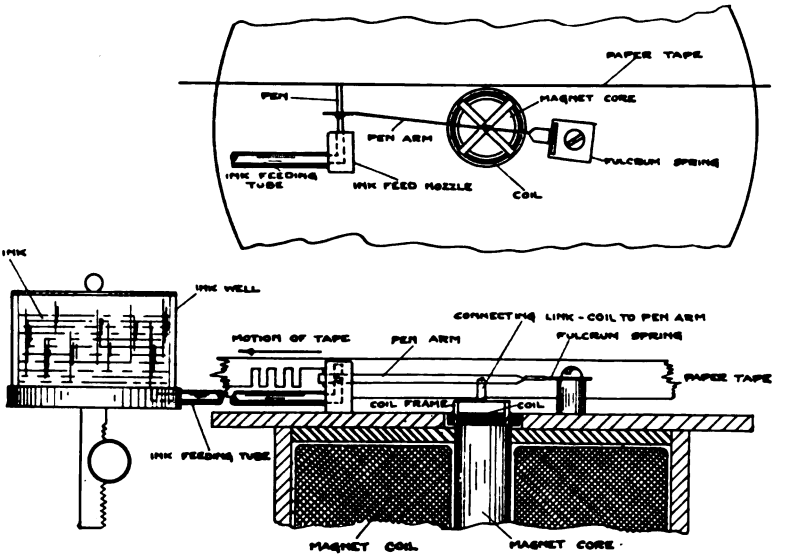

FIGURE 9—Essential Elements of Ink Recorder

The ink feeding arrangement consists of a piece of brass having a deep rectangular slot along the end near the pen, and is known as the ink feed nozzle. The slot is connected thru a hole to the side of the nozzle, where a rubber tube is attached. This tube connects to an inkwell fixed at one side of the recorder. The inkwell may be regulated in height, with respect to the ink feed nozzle, by means of a rack and pinion. The level of the ink in the nozzle is at the same height as its level in the inkwell; but since the slot is only about one-sixteenth of an inch (1.58 mm.) wide, surface tension keeps the ink from spilling out of the slot and it forms a long rectangular bead on the face of the nozzle into this bead the pen dips. If the magnet is energized and

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signal current passes thru the small coil, it is pulled upwards. The link therefore pushes the pen arm up; the pen moves upward in the bead on the face of the ink feed nozzle, supplying itself with ink, by capillary action, as it goes, and makes a vertical line on the slowly moving tape. When the signal current stops, the restoring force of the fulcrum spring sends the coil back to its starting position.

The recorder coil has about 600 turns, a direct current resistance of 1,000 ohms, and the pen will produce a full-size record ($\frac{1}{8}$ inch = 0.32 cm.) with about 4 milliamperes thru the coil up to a speed of 100 words per minute. For higher speeds, the fulcrum spring is changed, and with 8 milliamperes, 200 words per minute may be recorded.

The arrangement of parts here indicated makes it possible to provide a much simpler and more rugged instrument than the old type of siphon recorder, while at the same time gaining in speed and sensitivity. Instead of the wide air gap in the magnetic circuit, as in the old recorders, a narrow gap is used and a very powerful field can be provided with a relatively small magnetizing force. The moving elements are reduced to a minimum in weight and size, giving the instrument high speed capability and sensitivity. In place of the long breakable glass siphon, a short metal one is used, which is made up as a unit with the pen arm. In case of trouble, a spare pen arm can be inserted in a few moments. All parts are easily dismounted and are also readily accessible for adjustment or repair without dismounting.

The commercial model of recorder is shown in Figures 10 (top view) and 11 (cross-section). On these it will be noted that n addition to the essential elements of Figure 10, there have been provided the following:

(a) Four threads, with height and tension adjustment screws, which are used to center the recorder coil.
(b) An adjustable tape guide, consisting of a brass form in which the tape is held taut and smooth, so as to afford a good writing surface for the pen.
(c) Clamps and adjustments for various parts.
(d) Brushes for cleaning paper dust from the tape before it enters the tape guide (to prevent clogging the pen).
(e) A glass-topped cover over the recording mechanism.
(f) A "damping device."

The last-named part requires some explanation, and is illus-

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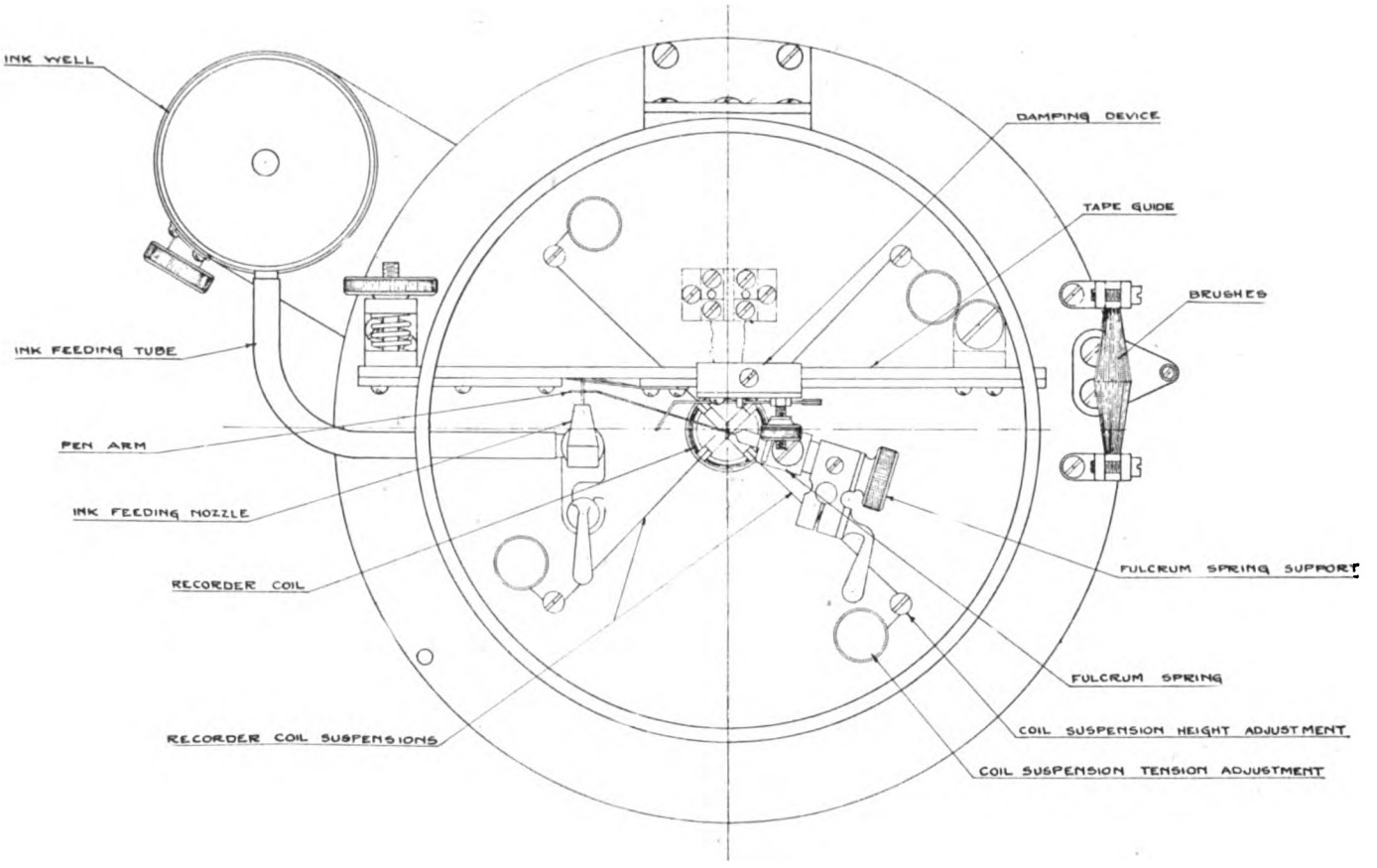

FIGURE—10 Ink Recorder, Commercial Model, Section

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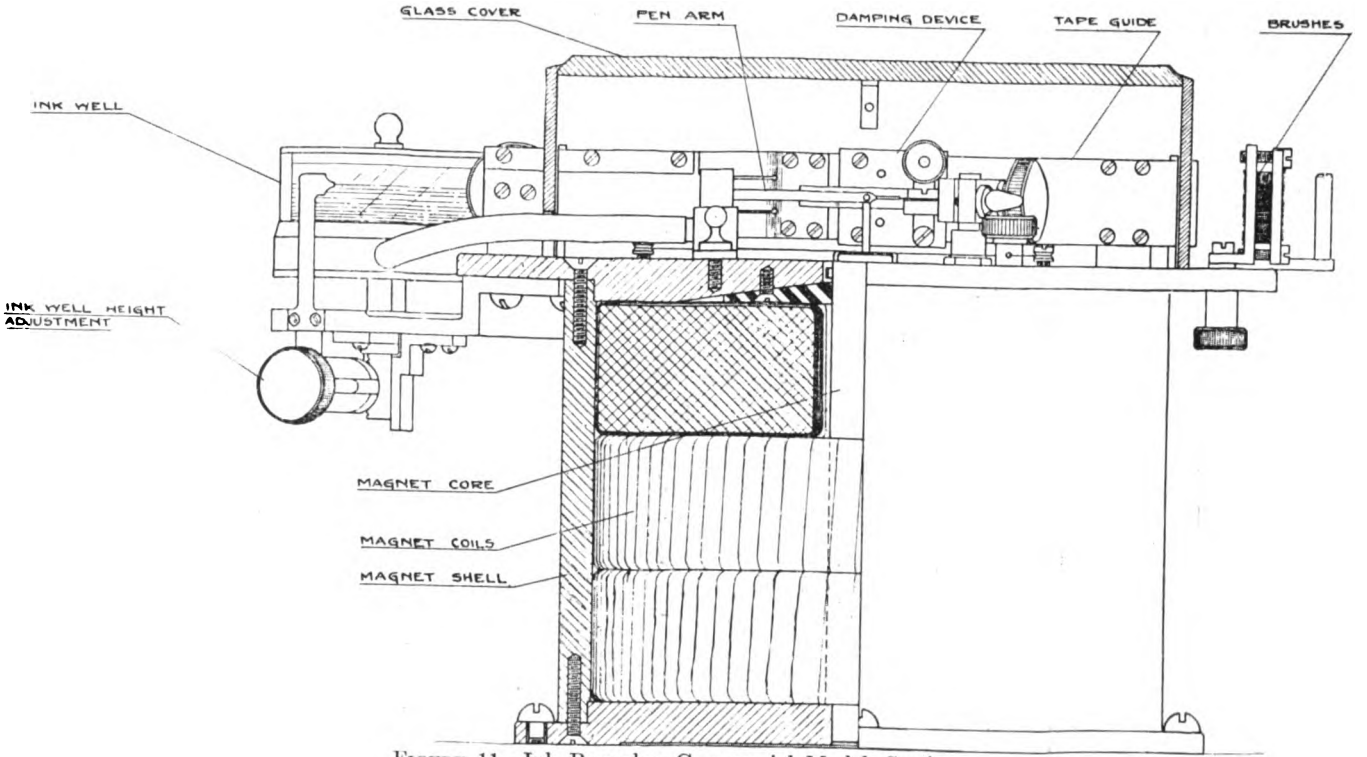

FIGURE 11—Ink Recorder, Commercial Model, Section

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trated in greater detail in Figure 12. Its purpose is to square off the tops and bottoms of dots and dashes, by stopping vibratory motions which would otherwise occur at the end of the stroke of the pen arm, due to the free mechanical oscillations of the recording system (coil, link, fulcrum spring, and pen arm)

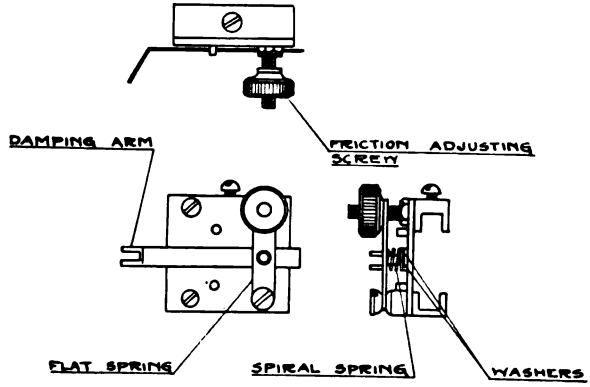

FIGURE 12—Ink Recorder Damping Device

This system has a natural frequency of about 35 cycles and a logarithmic decrement of about 0.7 (when equipped with a fulcrum spring for use below 80 words per minute;—for higher speeds a heavier spring is used having a considerably greater natural frequency). When allowed to operate without any damping other than that due to the friction of the paper against the pen, the record of the signal will appear as in Figure 13 (A). that is, at the end of its stroke the pen arm overshoots, and then falls back to the full amplitude or zero line, as the case may be In order to damp this tendency to overshoot, without, however, exerting a damping effect thruout the entire stroke (which would reduce the amplitude of the entire record), the damping device of Figure 12 was designed.

It consists of an aluminum arm pivoted at a point near one end, and cut into two prongs at the other end. A brass counter-

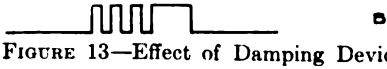

FIGURE 13—Effect of Damping Device

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weight on the short end serves to balance the arm about the pivot. The pen arm rests between the two prongs (see Figure 10), the space between these being sufficiently large so that the pen arm has a free movement of about 1/16 inch (1.6 mm.) without touching either prong. When the pen arm moves further than this, however, it strikes one or the other of the prongs and tends to carry the damping arm along with it. The freedom of movement of the damping arm is controlled by means of friction exerted by washers which press against the arm at its pivot, the pressure of the washers being regulated by means of a spiral spring which is compressed by a knurled-headed screw. Thus the motion of the pen arm is gradually checked as it approaches the end of its stroke and the signal can then be made to appear

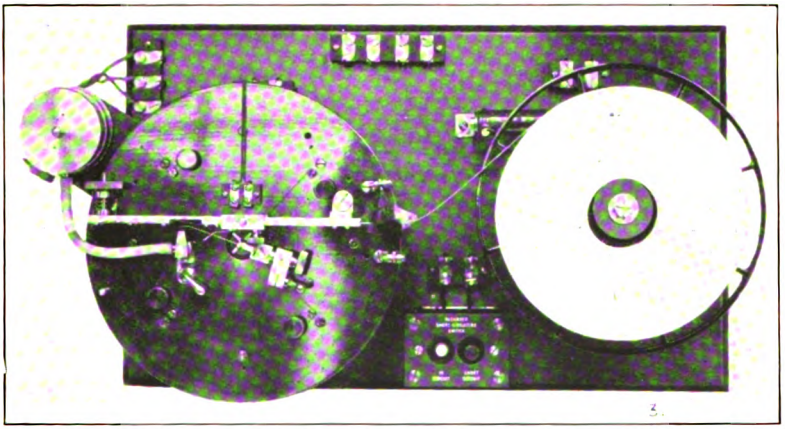

FIGURE 14—Ink Recorder and Tape Reel, Top View

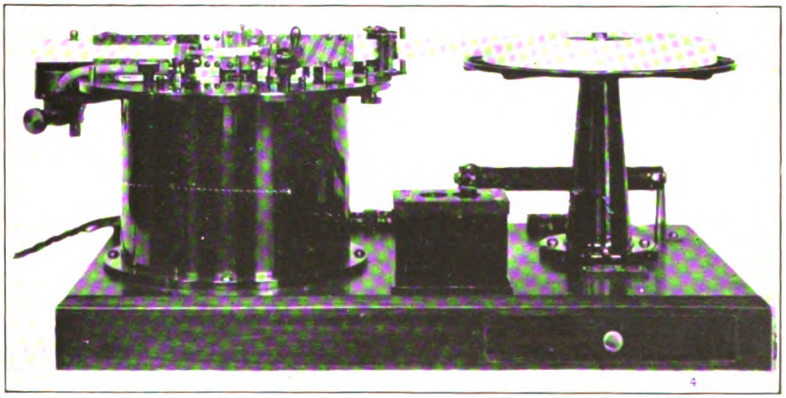

FIGURE 15—Ink Recorder and Tape Reel, Front View

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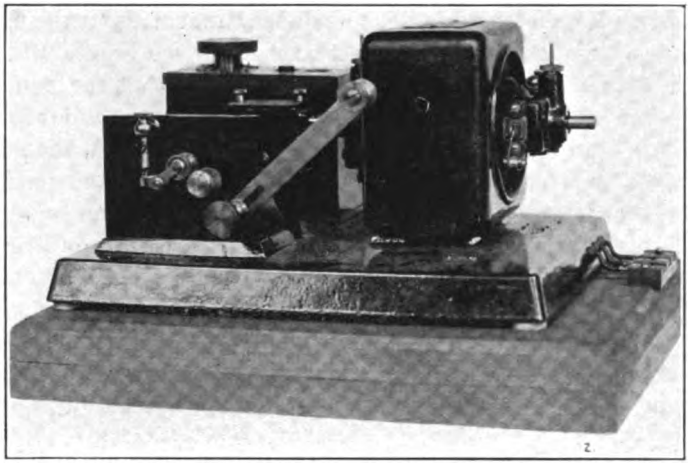

FIGURE 16—Tape Puller, Front View

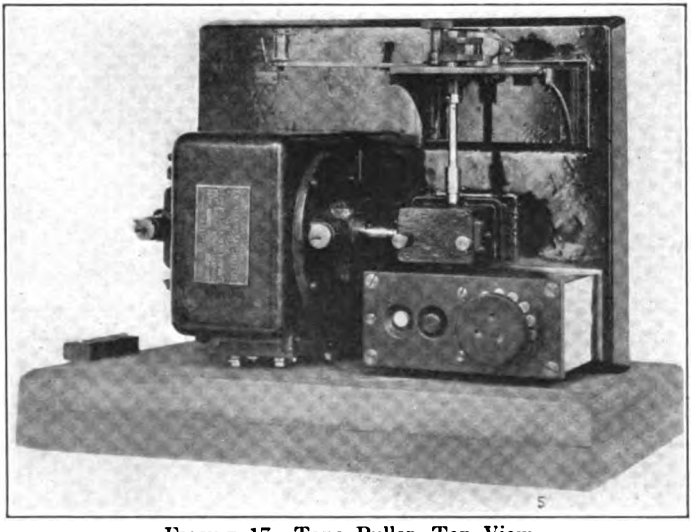

FIGURE 17—Tape Puller, Top View

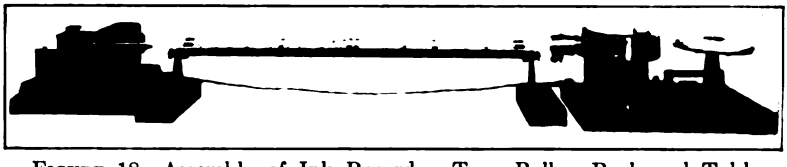

FIGURE 18—Assembly of Ink Recorder, Tape Puller, Reel, and Table

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square, as in Figure 13 (B). The finished commercial recorder and some of its accessory parts are shown in the photographs, Figures 14, 15, 16, 17, and 18. Figure 14 is a top view of the recorder assembled on a common base with the tape reel, Figure 15 the front view of the same, Figure 16 the machine for pulling the tape through the recorder (a standard commercial article known as a tape puller), Figure 17 a top view of the tape puller showing the motor speed control rheostat and gear box for reducing the motor speed to an appropriate value for the tape-pulling wheel, and Figure 18 an assembly of the recorder and tape puller with a "tape table" between them. The tape passes over the latter, and the operator's typewriter is placed in a well below the middle of the tape table, so that he may typewrite directly from the tape.

Amplifiers Associated with the Ink Recorder

While the development of the recorder was being carried on, experiments were conducted simultaneously to determine a suitable amplifier system, the input of which was to be connected to the radio receiving equipment in place of the operator's telephones and the output of which was to supply the recorder with a direct current of 2 to 4 milliamperes, thru the 1,000 ohm recorder coil. Aside from furnishing the required amplification, it was desired to utilize the amplifier circuits to secure as great a discrimination as possible between the signal audio frequency and strays.

For this purpose a number of amplifier circuits were set up and comparative records made on two identical recorders simultaneously, the signals from a local oscillator[1] being sent into a receiving antenna and their intensity regulated so that any desired ratio between signals and natural strays could be obtained. The amplifier under test was connected to one recorder, and a standard amplifier to the other recorder; the output of the receiving set being fed to both amplifiers at once. In this fashion an accurate and quick determination of the merits of any particular amplifier circuit could be made. This method of comparison yields much more dependable results than the method of taking sequential records on the same recorder with different amplifiers; strays are so exceedingly variable in their intensity and character from one minute to the next that the sequential method will lead to quite erroneous conclusions—as we found by experience.

[1] J. Weinberger and C. Dreher: "An Oscillation Source for Radio Receive Investigations," Proceedings of The Institute of Radio Engineers, volume 6, page 584, 1919.

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The amplifier circuits which were tested are shown in Figure 19. In every case, the tubes used were the Radio Corporation's type UV 202 (filament, 7.5 volts, 2.35 amperes, internal resistance 7,000 ohms), which are the standard receiving tubes in our stations; the plates were supplied from 220 volts, direct current, the local power lines being used thru suitable filters (to diminish line hum). The last amplifier tube always fed a step-down transformer, which was connected to a rectifier tube in series with the recorder.

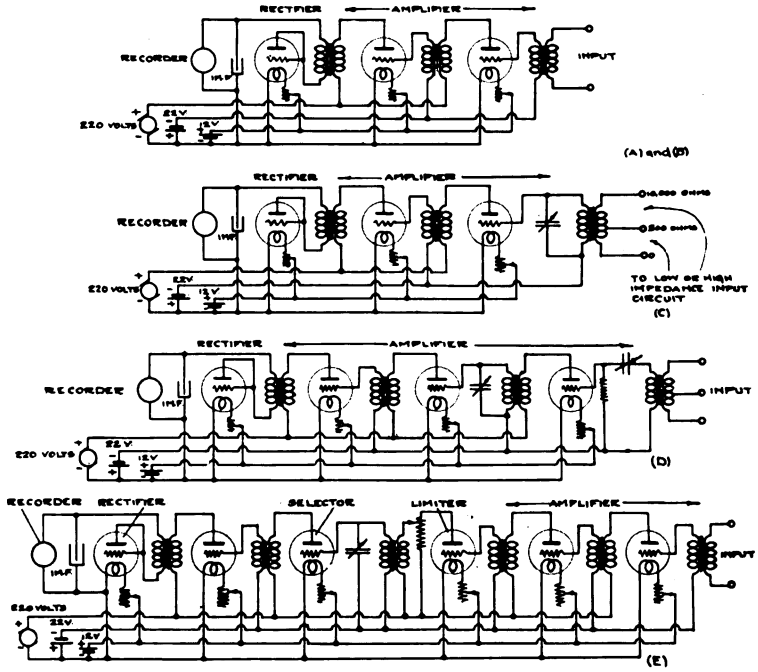

FIGURE 19—Experimental Ink Recorder Amplifiers

Five types of audio frequency amplifiers were tried, viz.:

(A) Two stages of untuned, air-core transformers known as the "Century" type, made by the Federal Telephone and Telegraph Company, Buffalo, New York, having the following constants: primary, 5,300 ohms direct current resistance, 3.4 henrys inductance, 9,700 turns of 3 mil (0.076 mm.) enameled wire; secondary, 37,000 ohms direct current resistance, 75 henrys inductance (at 800 cycles), 58,000 turns of 3 mil (0.076 mm.) enameled wire. This amplifier was built in order to deter-

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mine whether the signal-stray ratio of the air-core transformers was superior to that of iron-core transformers.

(B) The same as (A) but with closed *iron*-core transformers instead of air-core. These transformers were the Radio Corporations's type UV 712, having the following constants: Primary, 430 ohms direct current resistance, 3 henrys inductance at 1 milliampere and 800 cycles; secondary, 5,100 ohms direct current resistance. Ratio of turns, 9 to 1.

(C) One stage having a tuned transformer followed by one stage having an untuned transformer (type UV 712, as in case B). The tuned transformer consisted of two coils, the primary having 8,400 turns with a tap at 1,200 turns (for use in high or low impedance input circuits respectively); the secondary having 29,000 turns of 3 mil (0.076 mm.) enameled wire, on a common laminated iron core 3.5 inches (8.85 cms.) long and 0.5 inch (1.27 cm.) square. With a variable condenser of 0.001 microfarad capacity across the secondary the transformer could be tuned to any frequency in the range from 700 to 1,600 cycles. This transformer was the result of previous experiments along similar lines, and its tuning was sufficiently broad to take account of the normal fluctuations in frequency which might be expected at present in the reception of foreign alternator stations (approximately 100 cycles above or below a mean frequency of 1,000 producing a reduction of current to 75 per cent of full amplitude, or equivalent to a logarithmic decrement of about 0.6).

(D) One stage having a tuned transformer circuit of very high resistance, the resistance chosen being 0.7 of the critical damping resistance for the circuit; this followed by the same type of two-stage amplifier as in case of (C), that is, one tuned and one untuned stage. The purpose of this arrangement was to make a practical test of the following theory:

The natural frequency at which a circuit will oscillate, if shock excited, is given by the well-known expression

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}$$

However, if the circuit is subjected to a sustained alternating electromotive force, the maximum current will flow when

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC}}$$

That is, the resistance plays a part in determining the natural

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frequency of the transient circuit oscillations, but does not affect the "resonance" frequency. Hence, if the resistance is made as large as 0.7 of the critical damping resistance, the circuit will still oscillate, but at a frequency 0.7 that of the "resonance" frequency. With the particular tuned transformer used, this resistance was 300,000 ohms. Now, if this circuit was followed by a comparatively sharply tuned circuit, it was expected that the free oscillations due to strays would be at a frequency of 700 cycles when the signal frequency was 1,000 cycles, and the tuned circuit (set at 1,000 cycles) would respond more strongly to the signals than to the strays.

(E) An amplifier circuit involving "limiting" action, followed by audio frequency selection. This was based on the theory that if strong strays were reduced to an amplitude equal to that of the signal, by means of a "limiting" tube, then it would be possible to gain an advantage in signal-stray ratio by "picking out" the signal (which would have a definite audio frequency) with a sharply tuned circuit from amongst the strays (which would be of equal amplitude but of no definite frequency). To secure this result, a two-stage amplifier containing untuned air-core transformers was placed ahead of the limiting tube, and the latter was followed by an amplifier of type (C). A potentiometer in the plate circuit of the limiter controlled the amount of energy fed to the selecting circuit, so that the tube connected thereto would not be overloaded.

The conclusions drawn from numerous experiments with the above amplifiers were as follows:

(1) Air-core versus iron-core amplifying transformers (type A versus type B amplifier): No essential difference in behavior was found towards strays; it was concluded that the particular types of transformers tested could be used interchangeably in this work.

(2) Tuned versus untuned amplifier (type C versus type A): The tuned amplifier is moderately superior to the untuned one, on heavy strays. The advantage is not a great one, and during conditions which are suitable for high speed working (that is, light strays) there is no particular loss in dispensing with tuning. However, there is an advantage in the use of tuning, namely, that of discrimination against other interfering sustained audio frequencies, such as the compensation wave in the reception of arc transmitters, or the elimination of telephone line noises due to power line induction (which must be reckoned with in any system using wire line transfer of the received signals). It must

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also be remembered that the sharpness of tuning permissible in the amplifier transformer was limited by the fact that a certain amount of frequency fluctuation of the transmitter had to be reckoned with; it is possible that with very sharply tuned circuits greater advantages might be gained.

(3) Tuned amplifier type (C) versus tuned amplifier type (D): No appreciable difference in the behavior of these two types was found in the circuit under test and with this type of recorder; it was therefore concluded that there was no special advantage in the extra complication of type (D).

(4) Tuned amplifier type (C) versus limiting followed by audio frequency selection (type E): In the circuits shown, it was found that the strays had a slight tendency to mutilate the letters more badly with type (E) than with the simple tuned amplifier. This effect might have been due to the fact that a stray crash consists of many overlapping impulses, and when the signal was added on to these, the limiter temporarily passed on no signal for the audio frequency circuit to select. Hence, a letter would be broken more badly in this case than in the tuned amplifier employing no limiting ahead of the selecting circuit.

Therefore, it was decided that the tuned amplifier of type (C) was the best to use with the recorder for the present.

It is probable that a more extended investigation into the subject of amplifiers for the reduction of the stray-signal ratio would lead to profitable results, particularly on the assumption that a frequency constant to within one-tenth of one percent in foreign transmitters may be expected in the future; and this work is being continued.

Typical Ink Recorder Installations

The method of installation employed at outlying receiving stations is indicated in Figure 20. The recorder, tape puller, and tape carriage are mounted on a common table, and a typewriter well is placed so that the operator may copy directly from the tape. The amplifier is mounted on a panel conveniently near the recorder, so that tuning or other adjustments may be made while their effect on the record is observed.

In the central station at 64 Broad Street, New York City, the layout and method of operation of which is due to the Traffic Department of the Radio Corporation, the amplifier equipment is placed in an apparatus room separate from the operating room. Here a special amplifier is employed in which the ampli-

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fications necessary both for wire line transfer and recording are combined. The recorder is placed beside the operator.

The above method of having one operator copy directly from the tape is suitable up to a speed of about 45 words per minute. Above this speed several operators may read the tape in succession, in the manner used in cable offices. That is, one man is placed near the recorder, a second perhaps ten feet (3 meters) along the tape, and a third man ten feet further along. The

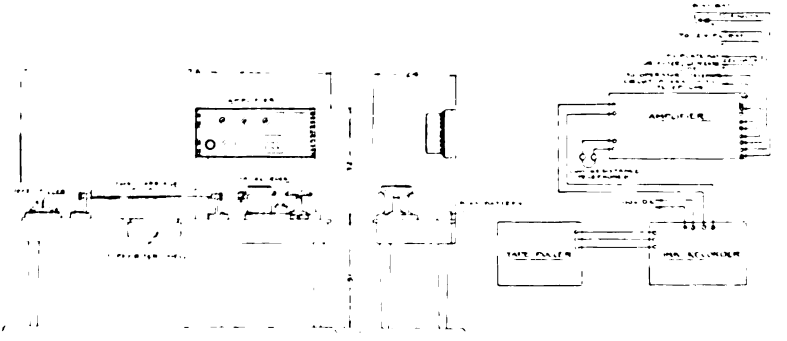

FIGURE 20 Ink Recorder System: Typical Installation at Outlying Stations

first man copies from the tape, which is moving faster than he can keep up with, until he reaches a point such that the signals are nearly out of easy sight. He then stops copying, marks the point on the tape at which he stopped, and starts in again as near the recorder end of the tape as he can see easily and marks on the tape the point at which he has started again. The second man then starts copying at the point at which the first man left off and copies the intervening material, either up to the point at which the first man started again, or else as far as he can. If he cannot read all the material omitted by the first man he also marks the point at which he left off, and the third man completes the copy of the omitted material. By this method the transcription of traffic at 100 words per minute by three men is readily possible.

Figure 21 is a photograph of part of the Broad Street operating room, in which some of the recorders may be plainly seen. In this office, a recorder is placed on each trans-oceanic receiving circuit, and, in addition, arrangements are being made to keep a record of the outgoing signals from each transmitter. This is accomplished by means of an antenna on the roof of the building, connected to receiving sets and recorders in the apparatus

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room; this equipment easily receives all of the local transmitting stations, and the signal leaving the sending operator's key or Wheastone transmitter may thus be directly compared with the signal radiated from the transmitting station's antenna. In this way, line or relay faults, trouble in the transmitting station, and the like, may be instantly noticed, and a check also kept on operating errors.

FIGURE 21—Part of Operating Room, Broad Street (New York City) Office Radio Corporation of America

TYPICAL RECORDS

In Figure 22 a number of typical tape records taken on the ink recorder are reproduced. These show plainly the speed capabilities of the instrument and the clearness of the records obtainable. The first three illustrations are of a series of test letters, "YI5," recorded at various speeds (these letters having been arbitrarily chosen because of the manner in which they display the operation of the instrument on various dot and dash combinations). All but one of the remaining illustrations are of various European transmitters recorded in the United States, while the last one is a record of the valve transmitter at Geneva (Switzerland), used on the Geneva-London radio circuit, taken on the ink recorder system at an English station.

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ACKNOWLEDGMENTS

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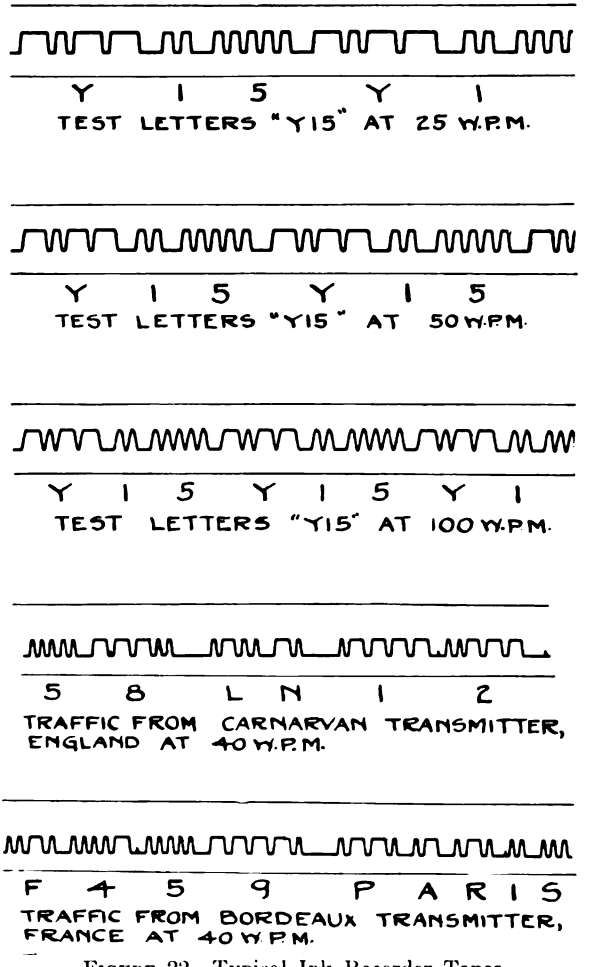
Y 1 5 Y 1
TEST LETTERS "Y15" AT 25 W.P.M.
Y 1 5 Y 1 5
TEST LETTERS "Y15" AT 50 W.P.M.
Y 1 5 Y 1 5 Y 1
TEST LETTERS "Y15" AT 100 W.P.M.
5 8 L N 1 2
TRAFFIC FROM CARNARVAN TRANSMITTER, ENGLAND AT 40 W.P.M.
F 4 5 9 P A R I S
TRAFFIC FROM BORDEAUX TRANSMITTER, FRANCE AT 40 W.P.M.

FIGURE 22—Typical Ink Recorder Tapes

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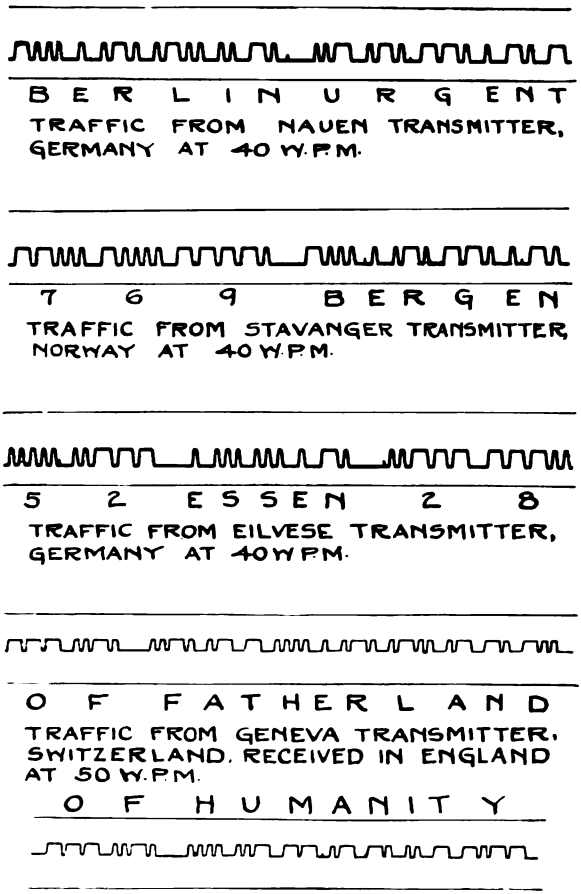
BERLIN URGENT
TRAFFIC FROM NAUEN TRANSMITTER, GERMANY AT 40 W.P.M.
7 6 9 BERGEN
TRAFFIC FROM STAVANGER TRANSMITTER, NORWAY AT 40 W.P.M.
5 2 ESSEN 2 8
TRAFFIC FROM EILVESE TRANSMITTER, GERMANY AT 40 W.P.M.
OF FATHERLAND
TRAFFIC FROM GENEVA TRANSMITTER, SWITZERLAND, RECEIVED IN ENGLAND AT 50 W.P.M.
OF HUMANITY

FIGURE 22—Typical Ink Recorder Tapes

SUMMARY: The requirements of a system to be used for recording high speed signals in commercial trans-oceanic radio telegraphy are discussed. Available methods are described and their advantages and disadvantages pointed out. The development of a new system, utilizing as the recording element a device known as the "Ink Recorder," is described, and typical installations as well as specimen records are shown.

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STYLOGRAPHIC RECORDERS. (MORSE INKER, SIPHON RECORDER, AND THE LIKE)

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A. Turpain: "Reception of Wireless Signals in Morse Script by the Aid of Extra Sensitive Relays," "Soc. Int. Elect. Bull.," volume 3, 3rd Series, page 299, 1913.

A. A. Campbell Swinton: "Recent Improvements in Recording of Signals in Wireless Telegraphy," "Electrician," volume 72, page 687, 1914. (Cable type siphon recorder with S. G. Brown's relays.)

Raymond Barker: "Recording Radio Signals," "Electrician," volume 72, page 783, 1914. (Morse inker and Orling cable relay.)

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the Creed Automatic System," "Wireless World," (London), volume 8, page 641, 1920.

F. Kiebitz: "Recent Researches in Radio Telegraphy," "Telegraphen und Fernsprechtechnik" (Berlin), volume 9, page 88, 1920. (Special relay and vacuum tube circuits with Morse inker.)

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DIGEST OF UNITED STATES PATENTS RELATING TO RADIO TELEGRAPHY AND TELEPHONY*

ISSUED FEBRUARY 28, 1922–APRIL 25, 1922

BY

JOHN B. BRADY

(PATENT LAWYER, OURAY BUILDING, WASHINGTON, D. C.)

1,408,053—R. J. Wensley, filed August 8, 1919, issued February 28, 1922.

HOT CATHODE APPARATUS for rectifying alternating currents. The rectifier employs double anodes and a cathode of relatively massive structure which is initially raised to incandescence by the passage of a relatively high voltage discharge by means of an auxiliary anode. Upon the attainment of incandescence at the main cathode, current flow takes place thereto from the main anodes and the resultant flow of working current suffices to maintain the cathode at the necessary temperature. By use of a saturation trannformer the auxiliary anode is substantially de-energized upon the initiation of load current flow, thus conserving the starting current.

1,409,352—S. E. Adair, filed February 20, 1918, issued March 14, 1922. Assigned to Western Electric Company, Incorporated.

ELECTRICAL COIL winding for radio apparatus. The winding comprises a plurality of symmetrical polygon turns, the adjacent turns having their dihedral angles angularly displaced with respect to each other to obtain a coil having a low distributed capacity. The coil is formed on a frame having a base and a plurality of spindles perpendicular to the base. The turns are supported on the spindles in such manner that adjacent turns do not lie next to one another but cross one another at a rather blunt angle at frequent intervals around the circumference of the winding.

1,409,717—P. C. Hewitt, filed October 29, 1915, issued March 14, 1922.

* Received by the Editor, May 3, 1922.

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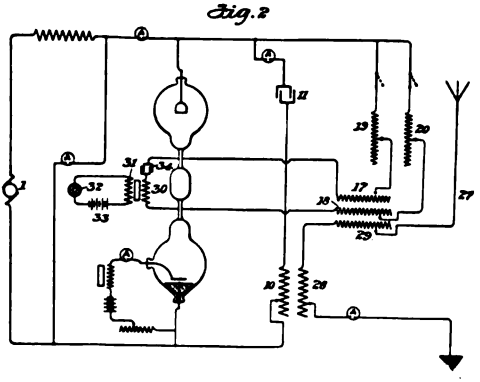

NUMBER 1,409,717—System of Transforming Energy

SYSTEM OF TRANSFORMING ENERGY, employing a pulsator illustrated in the drawings as of the mercury vapor type. The pulsator produces electric impulses in only one direction. An oscillating circuit is inductively related to the pulsating circuit, interlinked by a controlling inductive circuit. The oscillating circuit may be inductively coupled to an antenna ground system for transmission of signals.

1,410,062—G. Holst and E. Oosterhuis, filed May 10, 1920, issued March 21, 1922. Assigned to Naamlooze Vennootschap Philips' Gloeilampenfabrieken.

RECTIFIER FOR ALTERNATING CURRENTS, in which the electrodes are filamentary in form so that they can be used successively either as incandescent cathodes or as anodes. In case the incandescent filament is burnt out, one of the other electrodes can be used as a filament while the defective incandescent filament can be used as an anode.

1,410,730—R. R. Beal, filed Janary 5, 1920, issued March 28, 1922. Assigned to Augustus Taylor.

RADIO OSCILLATION GENERATOR. This patent relates to a construction of arc converter having a lower steel section and an upper steel section hinged thereto. The two sections form a closed shell with a magnet pole in each section. Each pole carries a field winding. The arc electrodes are mounted in the lower section and have their ends disposed between the magnet poles within the arc chamber.

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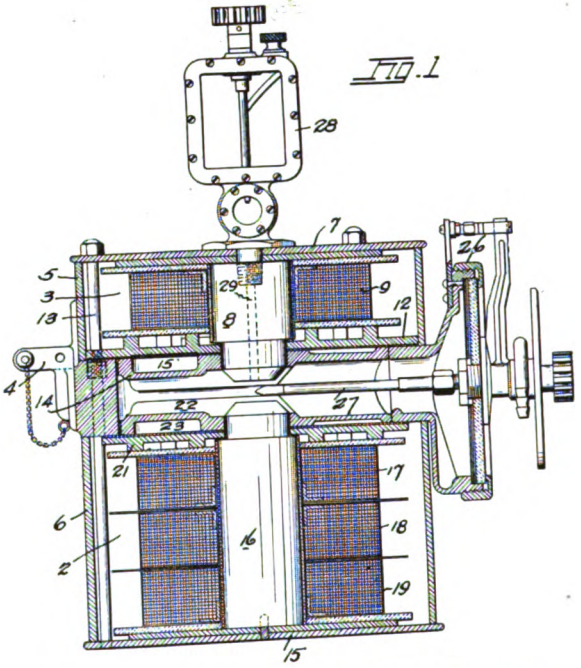
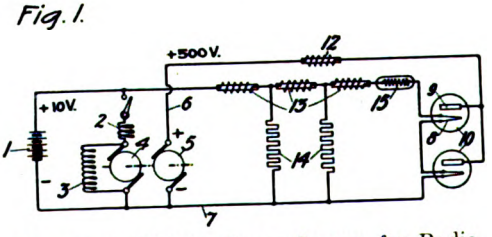


NUMBER 1,410,730—Radio Oscillation Generator

1,410,793—A. Bonnefont, filed November 9, 1920, issued March 28, 1922.

CRYSTAL DETECTOR FOR WIRELESS TELEGRAPHY. The patent shows a construction of crystal detector containing a crystal mounting and contact point entirely within an insulated stand. A mechanical arrangement is shown for moving the exploring point to different parts of the crystal.

1,411,814—H. M. Stoller, filed April 30, 1918, issued April 4, 1922. Assigned to Western Electric Company.



NUMBER 1,411,814—Power System for Radio Apparatus

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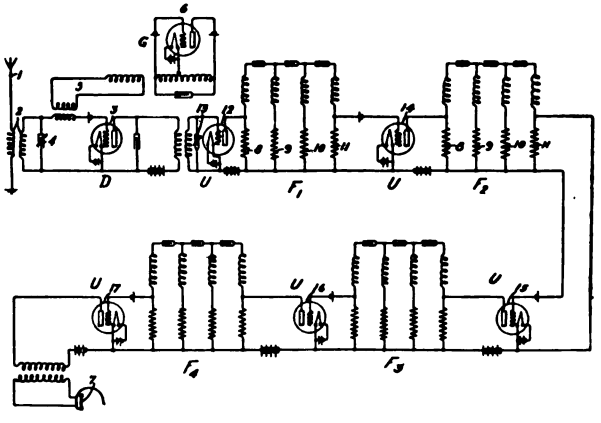
POWER SYSTEM FOR RADIO APPARATUS. The patent relates to an arrangement of motor generator for supplying filament-heating current and the plate voltage for aircraft radio transmitters. Light weight and small volume are features considered in this invention. The system includes a low voltage battery operating a motor and a high voltage generator driven by the motor. The battery supplies the filament-heating current for electron tube operation and the generator supplies the high voltage plate circuit for the electron tubes.

1,412,385—T. W. Case, filed November 17, 1920, issued April 11, 1922.

SIGNALING SYSTEM, for communicating by light rays. At the receiver the transmitted rays effect a light-responsive device producing an audible signal in a telephone receiver connected in an electron tube circuit. The invention makes use of a three-electrode tube containing a gas at a pressure between 0.1 of a millimeter of mercury and 5 millimeters of mercury.

1,412,567—J. Mills, filed December 30, 1916, issued April 11, 1922. Assigned to Western Electric Company, incorporated.



NUMBER 1,412,567—Means for and Method of Wave Transmission

MEANS FOR AND METHOD OF WAVE TRANSMISSION. The invention relates particularly to a receiving circuit with means for eliminating impulsive or static disturbances. The circuit comprises an electron tube detector, a local generator coupled thereto, and a plurality of recurrent network connected between stages

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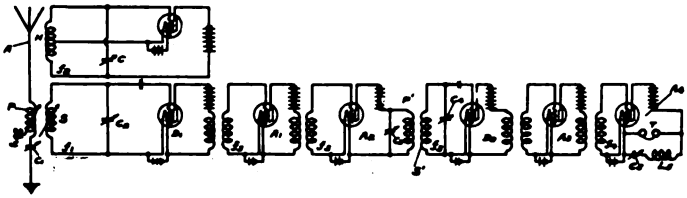
of electron tube circuits, including the responsive device in the last output circuit. The networks comprise a plurality of sections, each including inductance, capacity and resistance. These circuits freely transmit the audio frequency signal currents but highly attenuate and substantially extinguish the audio frequency disturbing currents. The audio frequency interfering currents supplied by the detector 3 will be converted into pulses by means of the filters F^1, F^2, F^3, and F^4, which have their natural modes of vibration critically damped. The interfering currents are successively attenuated in each filter, and the plurality of filters connected in tandem insure that the attenuation may be sufficient to reduce the interfering currents to a negligible value. The audio frequency signaling currents, however, delivered by the detector 3, acting as forced vibration, are freely transmitted from the several filters, so that these signaling currents are received by the signal device 7 to the exclusion of the interfering currents.

1,414,232—A. H. Taylor, *et al.*, filed August 12, 1919, issued April 25, 1922.



NUMBER 1,414,233—Method of Receiving Radio Signals with the Compound Heterodyne

METHOD OF RECEIVING RADIO SIGNALS WITH THE COMPOUND HETERODYNE, in which a circuit is employed having a primary detector, stages of electron tube amplification after the detector, and then a secondary detector followed by a plurality of stages of electron tube amplification. A single local source of oscillations is arranged to act a plurality of times on a single received signal to produce a plurality of beat currents of different frequencies. The last beat current operates the telephone receivers.

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PROCEEDINGS OF
The Institute of Radio Engineers

Volume 10 AUGUST, 1922 Number 4

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CORRECTIONS

In the paper on "The Piezo-Electric Resonator," by W. G. Cady, which appeared in the April, 1922 issue of the PROCEEDINGS, page 83, the following corrections should be made:

Page 87, equation (6), for y read y_w.
Page 97, third line from the bottom, for "low" read "high."
Page 98, first line, for "lead" read "lag."
Page 98, line 22, for X read x.
Page 106, line 12 from bottom, for $4 l^2 f^2$ read $2 l f$.

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RADIO TELEGRAPHY*

By

Senatore Guglielmo Marconi, G.C.V.O., D.Sc., LL.D., Etc.

The first occasion on which I had the honor of speaking before the members of the American Institute of Electrical Engineers was of a very festive nature.

It is over twenty years ago, to be exact on January 13, 1902; (there was not then any Radio Institute in existence) and on that date, memorable for me, I was entertained by over 300 members of your Institute at a dinner at the Waldorf-Astoria in this City. I was offered that dinner following my announcement of the fact that I had succeeded in getting the first radio signal across the Atlantic Ocean.

Many men, whose names are household words in electrical science, were present, men such as Dr. Alexander Graham Bell, Professor Elihu Thompson, Dr. Steinmetz, Dr. Pupin, Mr. Frank Sprague, and many others.

The function was one I shall never forget, and displayed to the full American resource and originality, as only forty-eight hours' notice of the dinner had been given, but what has left the greatest impression on my mind during all the long twenty years that have passed is the fact that you believed in me and in what I told you about having got the simple letter "S" for the first time across the ocean from England to Newfoundland without the aid of cables or conductors.

It gives me now the greatest possible satisfaction to say that, in some measure, perhaps, your confidence in my statement was not misplaced, for those first feeble signals which I received at St. John's, Newfoundland, on the 12th of December, 1901, had proved once and for all that electric waves could be transmitted and received across the ocean, and that long distance radio-telegraphy, about which so many doubts were then entertained, was really going to become an established fact.

* Received by the Editor, June 16, 1922. Presented before the American Institute of Electrical Engineers and The Institute of Radio Engineers, New York, June 20, 1922. On this occasion, The Institute of Radio Engineers Medal of Honor was presented to Senatore Marconi in recognition of his pioneer work in radio telegraphy.

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You will easily understand my feelings and how very happy I am to have the honor of addressing you again tonight, and when I say that I will always treasure the recollection of the generous encouragement and valid support so heartily extended to me practically at the commencement of my career, when perhaps I most needed it, by such a distinguished and authoritative body as the American Institute of Electrical Engineers.

The subject of my lecture, "Radiotelegraphy," has become so vast and so complex that you will readily understand my difficulty as to where I shall begin and as to when I ought to stop. It would be quite impossible for me to descant at any length on present achievements in a country which in a very short time has made gigantic strides in the scientific development and practical application of the science and art of radiotelegraphy. Moreover, time will not allow me to do more than skim over only a very few of the many problems which have lately been solved, or which there is a good prospect of solving in the near future.

Although we have, or believe we have, all the necessary data for the generation, transmission, and reception of electrical waves, as at present utilized for radiotelegraphy, we are still far from possessing exact knowledge concerning the conditions governing the transmission, or rather the propagation, of these waves through space, especially across long distances.

I propose now to bring to your notice some of the recent results attained in Europe and elsewhere and to call your attention particularly to what I consider a somewhat neglected branch of the art; and which is the study of the characteristics and properties of very short electrical waves. My belief is always that, only by the careful study and analysis of the greatest possible number of well authenticated facts and results, will it be possible to overcome the difficulties that still lie in the way of the practical application of radio in the broadest possible sense.

A very great impulse has been given to radiotelegraphy and telephony by the discovery and utilization of the oscillating electron tube or triode valve based on the observations and discoveries of Edison and Fleming, of those of De Forest and of those of Meissner in Germany, Langmuir and Armstrong in America, and H. W. Round in England, who have also brought it to a practical form as a most reliable generator of continuous electric waves.

As the electron tube, or triode valve, or valve, as it is now generally called in England, is able, not only to act as a detector, but also to generate oscillations, it has supplied us with an arrangement which is fundamentally similar for both transmitter

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and receiver, providing us also by a simple and practical method with the means for obtaining beat reception and an almost unlimited magnification of the strength of signals.

A result of the introduction of the triode valve has been that the basic inventions which made long distance radiotelegraphy possible have become more and more valuable.

It may perhaps be of interest if I give some information as to the progress made by the Marconi Company in England, with the practical application of the triode valve.

It has been so far our practice to use a plurality of tubes in parallel at our long distance stations. High power has been obtained in practice up to 100 kilowatts in the antenna by means of a number of glass tubes in parallel, and for the present we are standardizing units capable of supplying 4 kilowatts to the antenna, in the numbers required and sufficient for each particular case.

Some difficulty was at first experienced in paralleling large tubes in considerable numbers, but no difficulties now occur with groups of sixty bulbs working on voltages of 12,000 on the plate.

I am told that no insurmountable difficulty would be encountered if it were desired to supply 500 kilowatts to the antenna from a number of these bulbs. (Figure 1.) The life of the bulbs has been very materially increased and the 4-kilowatt units are expected to have a life, which, based on a great number of tests carried out both in the laboratory and at our Clifden station, should be well in excess of 5,000 hours.

The development of single unit tubes of considerable power is also progressing. We have lately concentrated on the production of high power tubes made of quartz, and two sizes of each bulb are now being made, one for 25 kilowatts to the antenna, and another for 75 kilowatts, but it is not expected that the efficiency of the high power single units will be as good as that of the multiple units, and the work on the large tubes is being considered so far as experimental.

In transmission work a large amount of investigation has been carried out during the last two years on the efficiency of the circuits and in regard to the best way of utilizing the available energy.

Considerable increases in efficiency have been obtained in the aerial or antenna circuits and also in minimizing the losses in the attendant loading coils, and the latest results indicate that it is possible to obtain efficiency of radiation into space as high as fifty per cent. on wave lengths as long as 20,000 meters, when, in

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this particular case, towers of a height of 250 meters would, of course, have to be used, owing to the length of the wave.

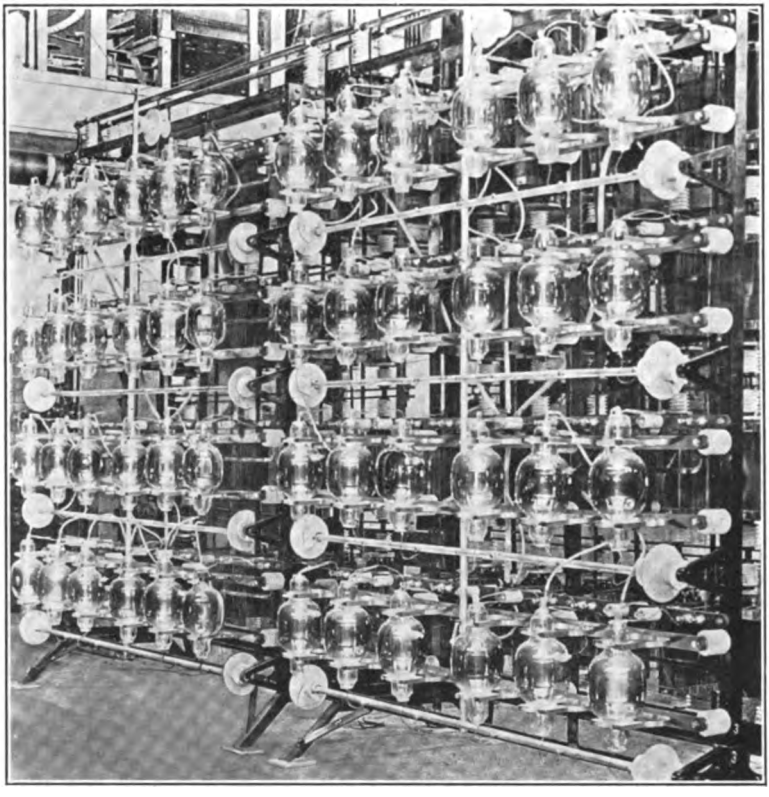

FIGURE 1—Tube Panel at Carnarvon

Very careful investigations have been carried out by Mr. H. W. Round, of all the losses in the loading coils and other parts of the tube circuits, and actual measurements on considerable power have shown that an over-all efficiency from the input power on the plates of the tubes to the aerial of seventy per cent. is possible with a complete avoidance of harmonics, that is, an efficiency from the power input to the plates of the tubes to actual radiation into space of about thirty-five per cent.

On shorter wave stations it is quite practicable still further to increase this efficiency, altho possibly it is hardly worth the extra expense involved. We have at present one station in England working on a 3,000 meter wave length with a height of mast of

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100 meters which has an efficiency from plates to radiation into space of 40 per cent.

Aside from the question of efficiency, great attention has been paid to maintaining an extremely constant frequency, and this can now be guaranteed to an extraordinary degree of constancy. Simple and reliable methods of high speed keying have been developed which on the shorter waves can be used up to over 200 words per minute, and on the longer waves to whatever speed the aerial constants will permit.

In high speed transmission, we are maintaining public services at 100 words per minute to two places in Europe, namely, Paris and Berne, using a single aerial transmitter with two wave lengths on the same aerial, and altho the operation uf utilizing a single aerial for two wave lengths is not an advisable one for high power work, it has certain points to recommend it in medium power work, where the consequent loss of efficiency can be made up for by a slight increase of power.

These two waves are working duplex to both Paris and Berne and practically all traffic is taken on printing machinery, altho there are occasions when, because of static, reception has to be done on undulator tape, and in some rare cases, on the telephones, by sound.

The reception at these shorter distance stations is carried out by means of a cascade arrangement of high and low frequency tuned amplifier circuits attached to the directional aerial system of the Bellini type, arranged for unidirectional reception when necessary. Very great care is taken in the receiving circuits to shield them so that the tuned circuits come well into action and to prevent any direct effect or influence of the aerial on circuits other than those intended to be acted upon. The characteristics of all these circuits have been very accurately measured so as to give filter curves suitable to the required speeds of working, and the adjustments are easily performed by the operators. Aside from the protection from interference given by directional reception, a close filtering, and an element of saturation, no particularly sensational methods or ideas in regard to static elimination have been so far introduced into practice.

The careful measurement and study of the constants of all circuits in use and the design of more efficient circuits from the result of those measurements is being systematically carried out, but as a result of these investigations considerable improvements have suggested themselves, which will be applied in the future if certain appropriate means can be devised.

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The protection of receivers against the troubles of atmospherics or static can only be, and is likely to continue to be, a relative matter, as it is quite obvious that a static eliminator under certain conditions will cease to be effective, where the static arrives with much greater intensity than had been anticipated, and will also frequently fail when, in consequence of the weakness of the received signals, amplification has to be increased to any considerable extent.

It would be really interesting to know how much the increase in C. W. transmitters, the development in directional reception, and the improvements in tuning that has taken place during the last few years have really increased our speed of readability and reliability over given distances.

As the development has been gradual, the tendency is towards pessimism, but I think we are now able at the same expense to work at about 8 to 10 times the effective speed that we were able to work at in 1912 under the same atmospheric conditions.

Interference from other stations has, of course, enormously increased and this has perhaps somewhat checked the increase of speed, but fortunately prevention of interference from other radio stations is a very much easier problem than the prevention of the disturbances caused by natural electric waves, or static.

Amongst the different types of tube amplifiers used in modern radio receiving stations, the tuned high frequency and audio frequency amplifier is probably the one which excites the greatest technical interest. In fact, its selective qualities, combined with the comparatively better ratio of signal strength to interference which it secures, justifies such interest.

These advantages were fully realized by most radio workers during the war, and I do not think that at the time the Armistice was signed there remained many radio laboratories where some time had not been utilized in experimenting on that type of receiver.

If those researches were generally not quite successful in regard to preparing or fixing the design of practical apparatus, they however indicated that the main difficulty to be overcome was to combine considerable amplification with stability and that the solution of the problem became rapidly more difficult with the increase of the number of tubes used in cascade.

By stability, in this case, I mean the freedom from any sudden generation of oscillations in any part of the circuits of the amplifier.

In 1920, however, an important step was made by Mr. G. Mathieu, as to the path to be followed out in order to obtain a

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practical solution of the problem. This consisted in the design of a new type of air-core tuned intervalve transformer arranged in such a manner as to possess only an extremely small electrostatic capacity between the windings, and having its effective primary impedance about equal to the effective internal plate to filament resistance of the tube in use when the secondary circuit was brought into resonance with the frequency of the oscillations to be amplified.

The results achieved during the first tests of these new transformers appeared to be quite amazing, the amplification factor for one tube having passed suddenly from 5 to about 15 for the particular tube tested, whilst the stability proved incomparably better than what had been obtained previously, even when the grid of the tube was kept to a negative potential of 1 or 2 volts.

The same principle has proved quite as successful when applied to the design of iron-core low frequency transformers. In this case, however, it was found necessary to adopt an iron magnetic shunt between the windings so as to provide a sufficiently loose coupling between the primary and secondary circuits of the transformer. Recently, Mr. Mathieu has further improved the design of his high frequency transformer by making it astatic.

One of these new appliances including high frequency and low frequency tuned transformers has been used daily on my yacht during my trip from England to America and the results of the tests carried out on board fully confirm the reliability of the apparatus and its marked superiority over the ordinary type of amplifier.

It has been clearly realized by most radio workers for some years that the science of radiotelegraphy had reached a stage of development where mere guesswork had done nearly all that could be expected from it, and that the improvement and development of commercial telegraphic services over what we once considered exceedingly long distances necessitated some very definite knowledge on the following points:

FIRST: The strength of signals that can be relied upon with given arrangements over these distances, and

SECOND: The all-important question of the ratio of the strength of signals to that of the natural disturbances and interferences acting on the receiving station in various parts of the world.

First of all, suitable and reliable apparatus for the purpose of obtaining the necessary data on both these points had to be

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developed. This apparatus is now in systematic daily use in a good many far distant places, with the result that a vast amount of most valuable information is being collected, and is now coming to hand.

At these observation points, the signals from distant stations are measured at all times of the day and night, together with the strength of the interference of static, and also the direction or bearing from which the static appears to be coming.

The measurements are done in such a way that the power that would be required at the transmitting station to give readability is used as a measure of the static, as this is the actual thing a radio engineer requires for the proper calculation of his transmitting station.

It is a method which gives a very satisfactory and reliable result in practices, and which I think could well be used universally.

In short, this method consists in inducing in the aerial C. W. signals from the measuring apparatus, which signals are made equal to those received from the distant transmitting station. The voltage applied to the aerial can then be directly read off. An aerial of a standard size is used for the purpose, and from this the strength of the signals in microvolts per meter can be calculated. If the signals are then unreadable, due to static, the measuring apparatus is used to send to an operator at a standard rate of 20 words per minute, 5 letter code, and the voltage applied to the aerial from the local sender is increased until complete readability is obtained, thus the ratio of the new voltage applied to the aerial to that of the old voltage equal to that of the signals received gives at once a very correct estimate of how much the power of the transmitting station would have to be increased in order to insure readability. As this variation can be carried out on aerial systems giving direction diagrams the method is obviously of great practical utility.

The question as to whether it would or would not be possible to transmit radio signals right round the world as far as the Antipodes is one which has always fascinated me. In fact the distance to the Antipodes is the greatest possible useful distance that can be covered by radio on this little earth of ours, and from this point of view the question was also important as such a distance included all minor distances between all other places on earth.

Sixteen years ago at a lecture I delivered on the 3rd of March, 1905, before the Royal Institution in London I expressed the belief that if it were proved that transmission to the Antipodes

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were possible, the waves ought to go over and travel round different parts of the globe from one station to the other, and perhaps all converge and concentrate at the Antipodes, and in this way I thought it might be possible to send messages to such distant places by utilizing only a moderate amount of electrical energy; and at that lecture I also showed a model globe and tried to explain how I thought the waves would help each other if arriving in proper phase, or in other words, concentrate at places at or near the Antipodes of the sending station.

The results recently obtained and which go to show the relative facility with which radio signals can now be sent from England to Australia seems to indicate that there is something in the idea of the wireless waves traveling round the earth by various ways and reuniting at places near the Antipodes.

But still more interesting and precise data has been obtained during other more recent tests.

Two expeditions, one to Brazil, and the other to New Zealand have carried out a number of most interesting and instructive observations, and although complete reports have not yet been received, I think it will nevertheless be of interest if I give you the results of some of their important tests.

The expedition to Brazil of which Mr. H. H. Beverage, of the Radio Corporation of America, Mr. N. W. Rust, of Marconi's Wireless Telegraph Company of England, and Mr. W. Eichkoff and Dr. A. Esau of the Gesellschaft fur Drahtlose Telegraphie (Telefunken) of Berlin formed part, has just completed a series of observations at various points on the Atlantic Coast of South America, where the intensity of the signals from European and other stations has been observed and measured at all times of the day and night, and where also the direction and intensity of atmospherics or static has been equally observed and recorded over considerable periods of time.

Another expedition under the direction of Mr. E. Tremellen, of the English Marconi Company, has just completed its work in measuring signals from all European and American high power stations, on a journey between England and New Zealand via the Panama Canal, and from the mass of information obtained on both day and night signals it should be possible, among other things, to reconstruct the attenuation formula. Incidentally, I may say that the signals exceed greatly in strength what should be expected according to the Austin-Cohen formula, otherwise super-long distance working would not be a practical proposition.

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Complete measurements from England to the Antipodes have been made on the Carnarvon, Nauen, Bordeaux, and Hanover signals; and also in Brazil on the American high power stations and on the U. S. Naval station, N. P. O. at Cavite (Philippine Islands).

In both these expeditions to Brazil and New Zealand the fact has been noted definitely and independently, and I think for the first time that signals from stations at very great distances do not always retain their direction along one great circle, but reach the receiver from either way or various ways round the earth.

These important observations were made by means of loop aerial direction finders arranged so as to give the well known heart shape diagram and the very interesting fact has been recorded independently by both expeditions, that on many occasions during what might be called a transition period, when the wave is changing from one way round the earth to another way round, the two or more sets of waves when received on a simple vertical aerial produced fairly slow beats resembling Morse signals, caused by the mutual interference or addition of the two sets of waves, whereas on the direction finder heart shape diagram arrangement, the signals were quite steady and normal when it was turned so as to receive only from one way or the other.

Of course it should be noted that when one is very near to the Antipodes there is only such a slight difference between any of the great circles leading from the sending station that the constancy of direction is not maintained, but this direction seemed to keep definitely true at distances of about 2,000 miles from the Antipodes.

The observers noted American signals from Radio Central and from Tuckerton coming from a direction which indicated that they preferred to travel a distance of three quarters of the way round the earth, rather than come by the shortest way round. Also, according to the reports received from the observers on other occasions at or near the Antipodes of the English or German stations, the direction finder often indicated the signals as coming from directions all round.

Another interesting and rather extraordinary result was noted on several occasions, according to the report of Mr. Tremellen from Rocky Point, New Zealand, where during last March the signals from Nauen appeared to travel to him via the South Pole, whilst those from Hanover, also situated in Germany, and not very far from Nauen, appeared to prefer to travel via the North Pole.

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A much more complete and exhaustive series of observations at fixed stations in Australia is now being made so as to obtain if possible all the variations from one period of the year to the other.

It seems to have been definitely ascertained in a general way that the sources of bad atmospheric disturbances, or static, are situated chiefly over land, but observations in Brazil indicate that a type of static known as "grinder" is a disturbance originating a long way off and coming from a direction which indicates the African Coast and at a time of the day when static there would be at a maximum, whereas a very violent "click" type of static came from a direction indicating its source as being nearby in South America.

During my present journey across the Atlantic, on board the Yacht *Elettra*, we noticed that up to about half way across (apart from the effects of local storms) static interference appeared to be coming mainly from the European and African continents, while at more than half way across they were coming from Westerly directions, that is, from the American continent.

The changing over of the direction of origin of these disturbances has also been noted under similar circumstances by Mr. Tremellen in crossing the Pacific.

It is very fortunate for the North Atlantic trans-Atlantic radio service, carried out at stations in North America and Europe, particularly for those in Western Europe, that this strong nearby type of static comes from directions which greatly differ from those from which one has to receive, and that the continents which lie in the direction of the sending stations are so far distant and sufficiently temperate as not to project troublesome static to the receiving stations on the other side of the ocean.

Another fact which can be fairly well deduced from these tests over very great distances is that transmission from West to East is apparently easier than from East to West, and shows the necessity for qualifying or modifying the transmission formula for great distances.

A scientific paper giving the results of measurements and of all the work carried out and observations made in these two expeditions will shortly be published.

I shall now deal with another and most important branch of the science of radiotelegraphy; a branch which I might say has been for a long time most sadly neglected. It concerns the use that can be made of very short waves, especially in regard to

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their application to directional radiotelegraphy and radiotelephony.

Some years ago, during the war, I could not help feeling that we had perhaps got rather into a rut by confining practically all our researches and tests to what I may term long waves, or waves of some thousands of feet in length, especially as I remembered that during my very early experiments, as far back as 1895 and 1896, I had obtained some promising results with waves not more than a few inches long.

The study of short waves dates from the time of the discovery of electric waves themselves, that is, from the time of the classical experiments of Hertz and his contemporaries, for Hertz used short electric waves in all his experiments, and also made use of reflectors to prove their characteristics and to show among many other things that the waves, which he had discovered, obeyed the ordinary optical laws of reflection.

As I have already stated, short electric waves were also the first with which I experimented in the very early stages of wireless history, and I might perhaps recall the fact that when, over 26 years ago, I first went to England, I was able to show to the late Sir William Preece, then Engineer in Chief of the British Post Office, the transmission and reception of intelligible signals over a distance of 1¾ miles by means of short waves and reflectors (Figures 2 and 3), whilst, curiously enough, by means of the antenna or elevated wire system, I could only get, at that time, signals over a distance of half a mile.

The progress made with the long wave or antenna system, was so rapid, so comparatively easy, and so spectacular, that it distracted practically all attention and research from the short waves, and this I think was regrettable, for there are very many problems that can be solved, and numerous most useful results to be obtained by, and only by, the use of the short wave system.

Sir William Preece described my early tests at a meeting of the British Association for the Advancement of Science, in September, 1896, and also at a lecture he delivered before the Royal Institution in London on the 4th of June, 1897.

On the 3rd of March, 1899, I went into the matter more fully in a paper I read before the Institution of Electrical Engineers in London, to which paper I would recall your attention as being of some historical interest.

At that lecture I showed how it was possible, by means of short waves and reflectors, to project the rays in a beam in one

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direction only, instead of allowing them to spread all around, in such a way that they could not affect any receiver which happened to be out of the angle of propagation of the beam.

I also described tests carried out in transmitting a beam of reflected waves across country over Salisbury Plain in England, and pointed out the possible utility of such a system if applied

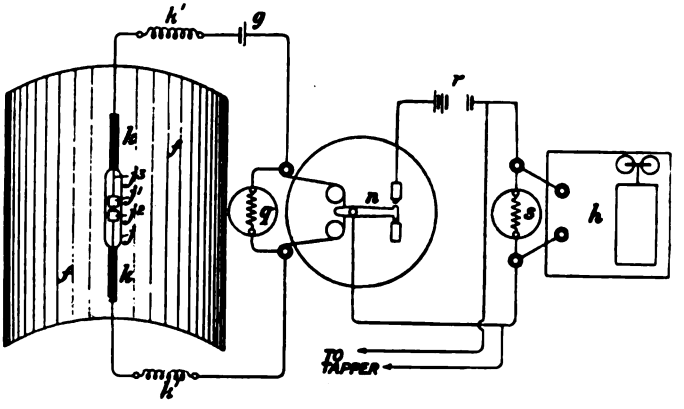

FIGURE 2—Early Short Wave Directional Receiver

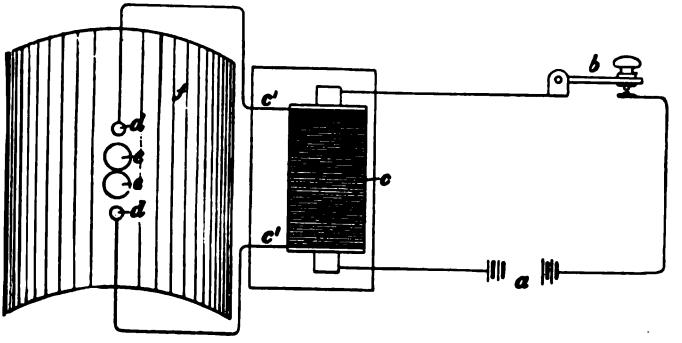

FIGURE 3—Early Short Wave Directional Transmitter

to lighthouses and lightships, so as to enable vessels in foggy weather to locate dangerous points around the coasts.

I also showed results obtained by a reflected beam of waves projected across the lecture room, and how a receiver could be actuated and a bell rung only when the aperture of the sending reflector was directed towards the receiver.

Since these early tests of over twenty years ago practically no research work was carried out or published in regard to short waves, so far as I can ascertain, for a very long period of years.

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Research along these lines did not appear easy or promising; the use of reflectors of reasonable dimensions implied the use of waves of only a few meters in length, which were difficult to produce, and, up to a comparatively recent date, the power that could be utilized by them was small. This and the fact of the very high attenuation of such waves over any distance of land or sea, gave results which appeared to be very disappointing.

The investigation of the subject was again taken up by me in Italy early in 1916 with the idea of utilizing very short waves combined with reflectors for certain war purposes, and at subsequent tests during that year, and afterwards, I was most valuably assisted by Mr. C. S. Franklin, of the British Marconi Company.

Mr. Franklin has since then followed up the subject with great thoroughness and the results obtained have been described by him in a paper read before the Institution of Electrical Engineers in London on the 3rd of April, 1922.

Most of the facts and results which I propose to bring to your notice are taken from Mr. Franklin's paper.

The work carried out in experimenting with these waves in 1916, was most interesting, as it was like going back to the very early days of wireless, when one had a perfectly clear field.

The waves used had a length of 2 meters and 3 meters. With these waves, disturbances caused by static can be said to be almost non-existent, and the only interference experienced came from the ignition apparatus of automobiles and motor boats. These machines apparently emit electric waves from near 0 to about 40 meters in length, and the day may come when they will perhaps have to have their ignition systems screened, or carry a Government license for transmitting.

Incidentally I might mention that one of these short wave receivers will act as an excellent device for testing, even from a distance, whether or not one's ignition is working all right. Some motorists would have a shock if they realized how often their magnetos and sparking plugs are working in a deplorably irregular manner.

During my tests in 1916, I used a coupled spark transmitter, the primary having an air condenser and spark in compressed air. By these means the amount of energy was increased and the small spark gap in compressed air appeared to have a very low resistance.

The receiver at first used was a crystal receiver, whilst the reflectors employed were made of a number of strips or wires

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tuned to the wave used, arranged on a cylindrical parabolic curve with the aerial in the local line.

The transmitting reflector was arranged so that it could be revolved and the effects studies at a distance on the receiver.

Mr. Franklin has calculated the polar curve of radiation into space (Figure 4), in the horizontal plane, which should be obtained from reflectors of various apertures, by assuming that the waves leave the reflector as plane waves of uniform intensity,

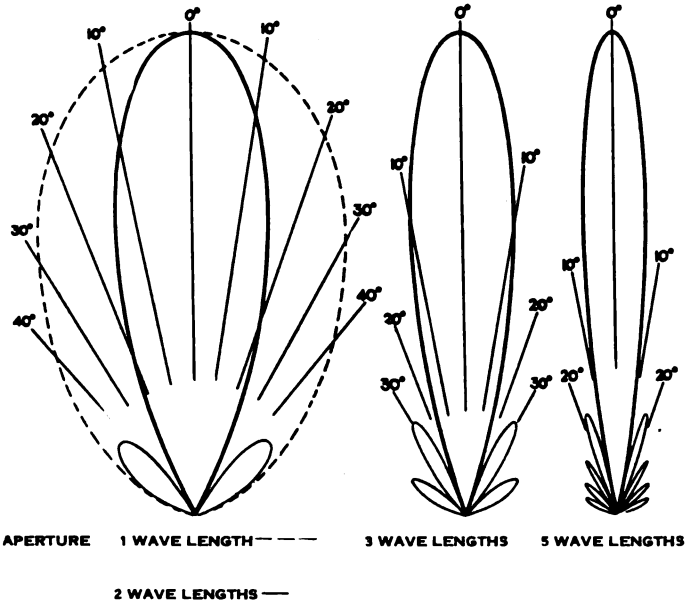

FIGURE 4—Calculated Polar Curves of Reflectors

having a width equal to the aperture of the reflector. The calculated curves agree very well with the observed results. In Figure 4 are shown the calculated curves for reflectors having apertures equal to 1, 2, 3, and 5 wave lengths.

Reflectors with apertures up to 3½ wave lengths were tested, and the measured polar curves agreed very well indeed with the calculated values.

The Italian experiments showed that good directional working could always be obtained with reflectors properly proportioned in respect to the wave length employed, and with the apparatus then available the range obtained was six miles.

The tests were continued in England at Carnarvon during 1917. With an improved compressed air spark gap transmitter,

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a three meter wave, and a reflector having an aperture of two wave lengths and a height of 1.5 wave length, a range of over 20 miles was readily obtained with a receiver used without a reflector.

In 1919 further experiments were commenced by Mr. Franklin at Carnarvon for which electron tubes or valves were used to generate these very short waves, the object being to evolve a directional radiotelephonic system.

A 15 meter wave was chosen, which could quite easily be generated by the type of electron tube employed.

After overcoming a few practical difficulties, very strong and clear speech was received at Holyhead 20 miles away. Longer distance tests were next undertaken and a receiving set of apparatus was installed on one of the mail boats running between England and Ireland.

During these tests clear speech was received all the way over to the Irish coast and into Kingstown Harbour at a distance of 78 miles from Carnarvon. The important fact was also noticed that there was no rapid diminution of the strength of signals after the ship had passed the horizon line from Carnarvon.

As a result of the success of these experiements it was decided to carry out further tests over land across a distance of 97 miles between Hendon (London) and Birmingham.

It was proved at once that, with reflectors at both ends, good and clear speech could be exchanged at all times between the two places.

The following are some particulars of the arrangements employed at Hendon and at Birmingham (Figures 5 and 6).

The power supplied to the tubes employed is usually 700 watts. The aerial is rather longer than half a wave length and has a radiation resistance which is exceedingly high. The efficiency input to the tubes to aerial power is between 50 and 60 %, and about 300 watts are actually radiated into space.

With the reflectors in use at both ends speech is strong and of very good quality. It is usually strong enough to be just audible with a ¼ to ½ ohm shunt across a 60 ohm telephone.

With both reflectors down and out of use, speech is only just audible with no shunt. Average measurements made by Mr. Franklin indicate that the value of the energy received when both reflectors are used is about 200 times that of the energy received without any reflectors.

These figures have been lately confirmed by local measurements taken round the stations.

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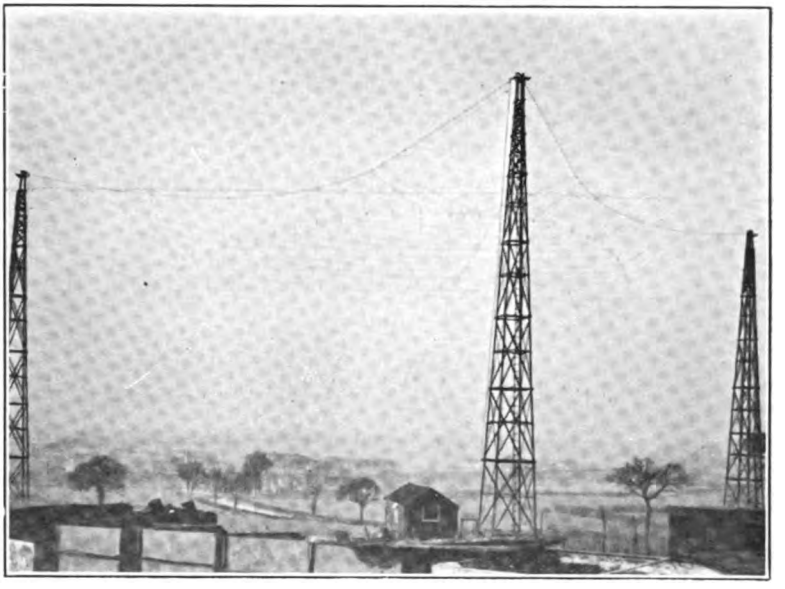

FIGURE 5—Directional Transmitter (Hendon)

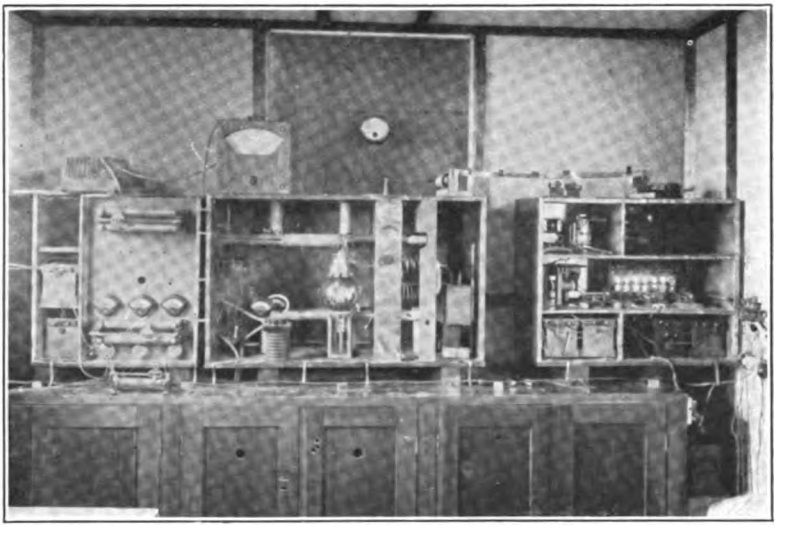

FIGURE 6—Experimental Short Wave Transmitter and Receiver at Hendon

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Figure 7 shows a measured polar curve of the field of Hendon station taken in the vicinity of the reflector. It is rather unsymmetrical in consequence perhaps of the ground being on a slope, and owing to local reflection from trees and wires.

It has occurred to some of my assistants that a polar curve taken locally round the station may not be the same as a curve

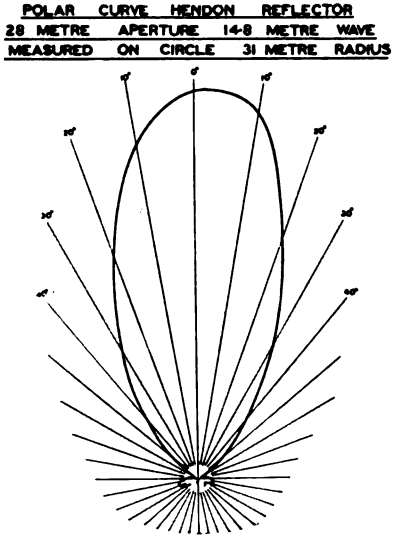

FIGURE 7—Polar Curve of Hendon Reflector

taken at a distance, and that at a distance the directional effect may be lost. I am, however, in agreement with Mr. Franklin that such is not the case.

Experiments carried out with revolving reflectors, which make it easy to read measurements at any distance, prove that the polar diagram for a given reflector and wave length is practically constant at all ranges.

By means of suitable electron tubes or valves, it is now quite practicable to produce waves from about 12 meters and upwards utilizing a power of several kilowatts, and it is also practicable to utilize valves in parallel.

During the continuous wave tests at Carnarvon, it was found that reception was quite possible on the transmitting aerial whilst the transmitter was operating.

This system is being used successfully for duplexing between Hendon and Birmingham, as it avoids all switching.

Reflectors besides giving directional working, and econo-

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mizing power, are showing another unexpected advantage, which is probably common to all sharply directional systems. It has been noted that practically no distortion of speech takes place, such as is often noticed with non-directional transmitters and receivers, even when using short waves.

The results between Hendon and Birmingham easily constitute a record for radiotelephony in respect to the ratio of distance to wave length, as Birmingham, it may be interesting to note, is 10,400 wave lengths from Hendon.

We consider, however, that these results represent only what could be obtained from a first attempt, and not what could now be done after the experience gained.

It has thus been shown for the first time that electric waves of the order of 15 to 20 meters in length, are quite capable of providing a good and reliable point to point directional service over quite considerable ranges.

In these days of broadcasting, it may still be very useful to have a practically new system which will be to a very large degree secret, when compared to the usual kind of radio.

The results obtained by reflectors appeared to be so good that I was tempted to try out my old idea of 26 years ago, and test the system as a position finder for ships near dangerous points. This is now being done in Scotland through the courtesy of Messrs. D. and C. Stevenson and of the Commissioners of Northern Lights. Trials are being carried out under the supervision of Mr. Franklin with a revolving reflector erected at Inchkeith Island in the Firth of Forth near Edinborough. The transmitter and reflector revolving, act as a kind of wireless lighthouse or beacon, and, by means of the revolving beam of electrical radiation, it is possible for ships, when within a certain distance to ascertain, in thick weather, the bearing and position of the lighthouse.

The experimental revolving reflector was erected and the first tests were carried out with the S. S. *Pharos* during the autumn of 1920 (Figure 8).

With a 4-meter wave spark transmitter, a reflector, and a single tube receiver, suitably tuned, on the ship, a working range of 7 miles was obtained.

The reflector was caused to make a complete revolution every two minutes, and a distinctive signal was sent every half point of the compass. It was ascertained on the steamer that this enabled the bearing of the transmitter to be accurately determined within ¼ point of the compass, or within 2.8 degrees.

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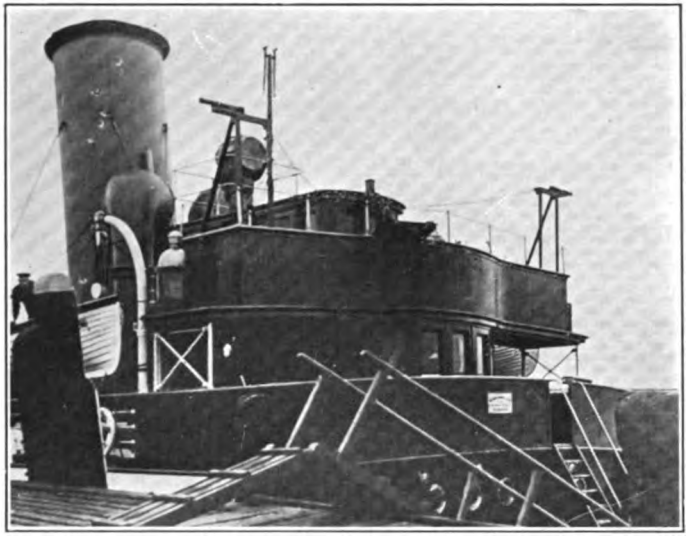

FIGURE 8—Short Wave Receiver on Steamship "Pharos"

At a later date a new reflector was designed and erected and is now being tested (Figure 12).

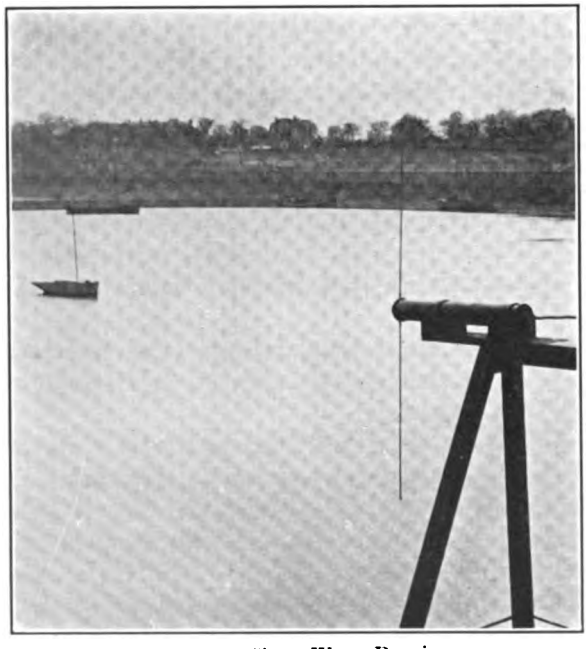

FIGURE 9—Short Wave Receiver

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Figure 10 shows measured polar curves taken recently with the new reflector. The curves were measured at a distance of 4 miles.

With the revolving beam the exact times of maximum signals

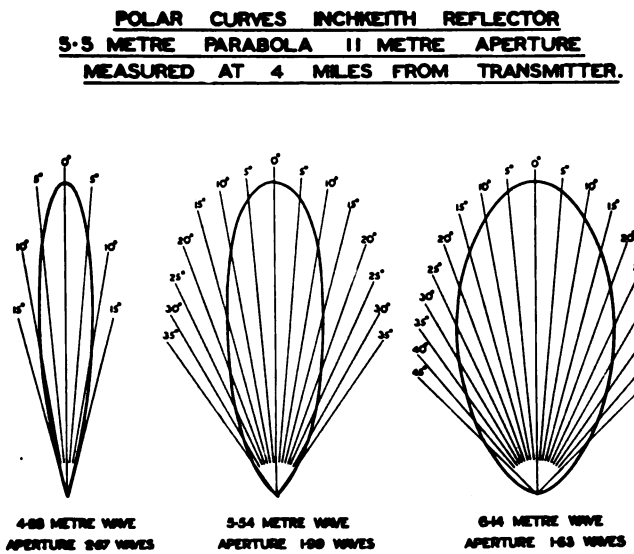

FIGURE 10—Polar Curves of Inchkeith Reflector

are not easy to judge, by ear, but the times of starting and vanishing are easy to determine, as the rate of rise and fall of the signals is extremely rapid. The time half way between these two times gives, with great exactness, the moment when the beam is pointing to the ship (Figure 11).

By means of a clockwork arrangement a distinctive letter is sent out every two points, and short signs mark intermediate points and half points; and this is done in practice by contact segments arranged on the base of the revolving reflector, so that a definite and distinctive signal is transmitted at every half or quarter point of the compass (Figure 12).

I will now try to show you the working of a roughly constructed 1-meter wave transmitter and reflector.*

The attenuation of these short waves over sea is so surpris-

*At this point, Senatore Marconi demonstrated the transmission of 1-meter continuous waves from a parabolic reflector of the type shown in Figure 3, and composed of parallel wires, over a distance of approximately 15 meters to a tube receiver with reflector similar to that of Figure 2. Absorption of the waves by a tuned resonator was also shown—EDITOR.

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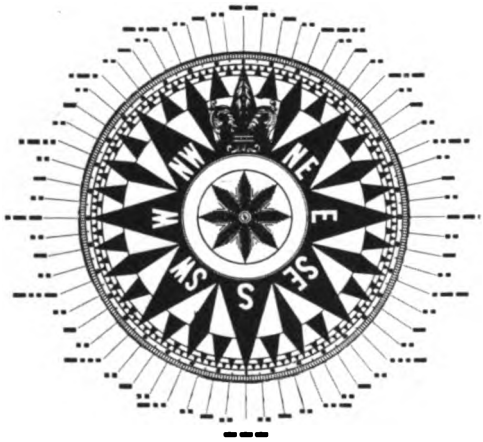

FIGURE 11—Compass Bearings with Letter Designations for Radio Direction Finding

ingly regular that a little experience enables distance to be judged by the strength of signals, and this can be measured by means of a potentiometer.

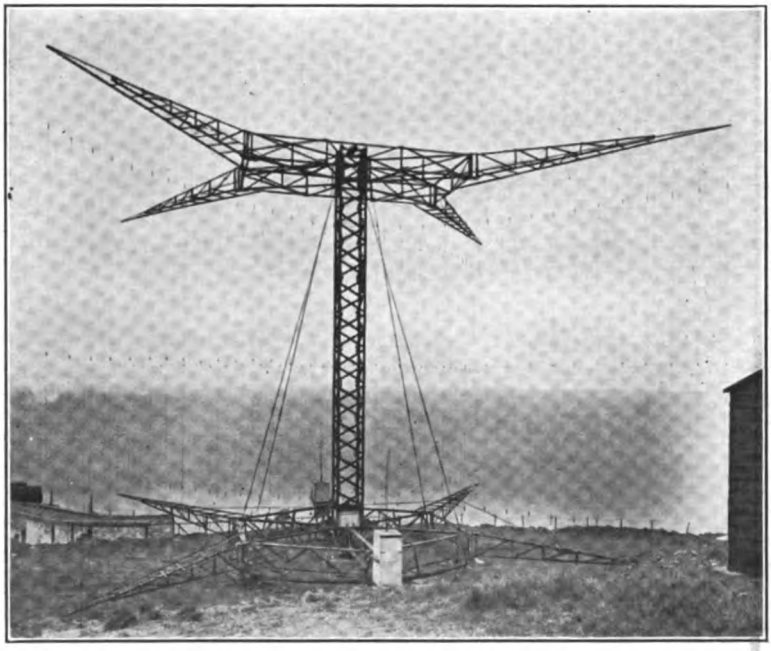

FIGURE 12—Rotating Short Wave Directional Transmitter, Inchkeith

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Before I conclude I should like to refer to another possible application of these waves which, if successful, would be of great value to navigators.

As was first shown by Hertz, electric waves can be completely reflected by conducting bodies. In some of my tests I have noticed the effects of reflection and deflection of these waves by metallic objects miles away.

It seems to me that it should be possible to design apparatus by means of which a ship could radiate or project a divergent beam of these rays in any desired direction, which rays, if coming across a metallic object, such as another steamer or ship, would be reflected back to a receiver screened from the local transmitter on the sending ship, and thereby immediately reveal the presence and bearing of the other ship in fog or thick weather.

One further great advantage of such an arrangement would be that it would be able to give warning of the presence and bearing of ships, even should these ships be unprovided with any kind of radio.

I have brought these results and ideas to your notice as I feel—and perhaps you will agree with me—that the study of short electric waves, although sadly neglected practically all through the history of wireless, is still likely to develop in many unexpected directions, and open up new fields of profitable research.

Having referred so lengthily to what is essentially a directional system, that is, a system that does not spread its waves all round, you will perhaps expect a few words from me before I bring this rather lengthy discourse to a close, on the subject of "Broadcasting."

No remarks from me or from anyone else are required to tell you what has already been done with radio in America, as a means of broadcasting human speech, and other kinds of sound which may also be entertaining if not always instructive.

In thousands of homes in this country there are radiotelephonic receivers, and intelligent people, young and old, well able to use them—often able to make them—and in many instances contributing valuable information to the general body of knowledge concerning the problems great and small of radiotelegraphy and radiotelephony.

But I think I am safe in saying that if radio has already done so much for the safety of life at sea, for commerce, and for commercial and military communications, it is also destined to

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bring new and, until recently, unforeseen opportunities for healthy recreation and instruction into the lives of millions of human beings.

ABSTRACT

The lecture first deals briefly with the early history of long distance radio communication.

The work carried out by the engineers and experts of the Marconi Company in England with electron tubes or triode valves shows that, according to their experience, greater efficiency can be obtained at present by a number of bulbs used in parallel than by the employment of large single unit tubes.

Information is given in a general way in regard to recent practice in the design and construction of receivers with the object especially of improving selectivity, reducing interference, and concerning the possible speed of working.

The lecture also deals briefly with results obtained at receiving observation stations situated in various far distant parts of the world, where it has been ascertained that radio signals arriving from high power stations situated at or near the antipodes of the observation stations, reach the receivers by various ways around the earth, not always following the shortest great circle route, and also that at such places the electric waves coming round by different ways do in certain cases increase this effect on the receivers whilst in others interfere with each other.

It has also been noticed that apparently transmission is easier from west to east than from east to west, and that it may be necessary to modify somewhat the transmission formula for long distances.

It has also been ascertained that the most troublesome atmospheric disturbances or static usually come from the continents and not from the oceans.

The lecture further deals with a study of short electrical waves and the results which have been obtained with such waves of a length from 1 meter to 20 meters, and describes tests which show for the first time that electric waves of under 20 meters in length, used in connection with suitable reflectors, are quite capable of providing a good and reliable point-to-point, unidirectional system of radio over quite considerable distances.

The application of this system as a direction finder in aid of navigation, and as a method for preventing collisions at sea, is also dealt with.

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RECEIVING MEASUREMENTS AND ATMOSPHERIC DISTURBANCES AT THE NAVAL RADIO RESEARCH LABORATORY, BUREAU OF STANDARDS, WASHINGTON, MARCH AND APRIL, 1922*

By

L. W. Austin

(United States Naval Radio Laboratory, Washington, D. C.)

(Communication from the International Union for Scientific Radio Telegraphy)

The observations in the tables, both signals and atmospheric disturbances, were made by comparing the telephone current due to the signal or disturbance, with that due to a known audio frequency emf. impressed on the telephone terminals. In the case of signals, the beat note is brought to the same pitch as the tuning fork vibrator which produces the comparison telephone current. Since this is impossible in the case of the disturbances, these are compared with the known telephone current which can just be heard with the telephones in such a position with respect to the ears that the disturbances are just audible.

The receiving system is frequently calibrated by measuring the telephone currents due to signals of known intensity with the telephone comparator. These known signals are in some cases sent from the Washington Navy Yard with a few milliamperes in the sending antenna, using the regular antenna for reception at the laboratory. In other cases some of the American stations of known effective height and antenna current, such as Marion, Sayville, or Long Island (New York Radio Central), are received on a low antenna. The relative effective heights of the two receiving antennas are determined by thermoelement reception of Arlington's arc. These calibrations indicate that for level country of medium conductivity, and wave lengths above 10,000 m., the attenuation of the signal is practically the same as for salt water, up to at least 400 miles (640 km.).

The average effective height of the regular receiving antenna during March and April was 15.1 m. (50 ft.). The height of the

* Received by the Editor, June 10, 1922.

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Field Intensity of Lafayette Station and Disturbances ($\lambda = 23{,}400$ m.) in March, 1922, in Micro-volts per Meter

Date	10 A. M.		3 P. M.	
	Signal	Disturbances	Signal	Disturbances
1	60.0	50	60.0	60
2	55.0	20	65.0	30
3	58.0	40	50.0	30
4	50.0	40	40.0	20
6	60.0	40	55.0	30
7	50.0	30	45.0	50
8	70.0	10	85.0	30
9	90.0	80	50.0	100
10	90.0	60	85.0	40
11	65.0	30	60.0	60
13	50.0	750	55.0	500
14	60.0	50	55.0	50
15	70.0	50	45.0	200
16	75.0	50	60.0	40
17	75.0	40	70.0	50
18	65.0	40	85.0	50
20	45.0	400	75.0	100
21	50.0	30	55.0	30
22	65.0	30	50.0	40
23	70.0	20	55.0	40
24	90.0	30	50.0	300
25	50.0	40	....	..
27	60.0	30	55.0	50
28	....	100	35.0	200
29	70.0	400	40.0	300
30	65.0	30	90.0	650
31	55.0	40	40.0	200
	1663.0	2530	1610.0	3250
Average	64.0	93.7	62.0	125.0

low antenna, used for receiving the stronger stations was 1.2 m. (4 ft.). Assuming 480 antenna amperes at Lafayette, and 380

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Field Intensity of Lafayette Station and of Disturbances ($\lambda = 23{,}400$ m.) in April, 1922, in Micro-volts per Meter

Date	10 A.M.		3 P. M.	
	Signal	Disturbances	Signal	Disturbances
1	60.0	30	50.0	50
3	55.0	40	60.0	60
4	55.0	30	45.0	300
5	45.0	300	60.0	500
6	65.0	80	55.0	150
7	75.0	80	45.0	200
8	60.0	100	75.0	150
10	60.0	300	30.0	400
11	90.0	40	75.0	500
12	110.0	20	45.0	30
13	95.0	40	50.0	60
14	20.0	2100	50.0	200
15	60.0	40	55.0	50
17	55.0	100	75.0	150
18	75.0	40	90.0	30
19	95.0	50	75.0	50
20	....	..	55.0	60
21	80.0	40	75.0	30
22	145.0	40	75.0	40
24	150.0	50	115.0	40
25	130.0	60	60.0	500
26	125.0	60	45.0	500
27	....	..	50.0	300
28	100.0	300	55.0	80
29	95.0	200	85.0	200
	1900.3	4140	1520.0	4630
Average	82.6	160	60.8	185

amperes at Nauen, the electric field intensity calculated from our formula (see also PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS, volume 10, page 158, June, 1922), is:

E (Lafayette) $= 31.5.10^{-6}$ volts/meter

E (Nauen) $= 15.3.10^{-6}$ volts/meter

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Field Intensity of Nauen Station and of Disturbances (λ = 12,500m.) in March, 1922, in Micro-volts per Meter

Date	10 A. M.		3 P. M.	
	Signal	Disturbances	Signal	Disturbances
1	38.0	20	....	..
2	30.0	15	....	..
3	26.5	15	26.5	20
4	26.5	8	....	..
6	34.0	10	26.5	20
7	22.5	8	....	..
8	34.0	8	34.0	15
9	38.0	30	....	..
10	38.0	40	30.0	50
11	26.5	10	....	..
13	30.0	300	30.0	200
14	34.0	20	....	..
15	30.0	20	38.0	30
16	34.0	40	26.5	20
17	45.0	20	19.0	15
18	26.5	10	....	..
20	....	..	....	..
21	22.5	10	26.5	15
22	30.0	8	26.5	10
23	45.0	8	....	..
24	49.0	15	38.0	150
25	34.0	15	....	..
27	26.5	15	30.0	20
28	34.0	20	26.5	50
29	68.0	80	30.0	100
30	34.0	10	....	..
31	7.8	100	13.0	80
	864.3	855	421.0	795
Average	33.2	32.9	28.06	53.0

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Field Intensity of Nauen Station and of Disturbances ($\lambda = 12{,}500$ m.) in April, 1922, in Micro-volts per Meter

Date	10 A. M.		3 P. M.	
	Signal	Disturbances	Signal	Disturbances
1	30.0	10	....	..
3	47.0	8	38.5	10
4	38.5	8	30.0	100
5	21.5	80	43.0	80
6	43.0	20	30.0	40
7	51.5	40	43.0	50
8	38.5	60	34.0	50
10	51.5	60	....	..
11	56.0	10	....	..
12	68.5	8	26.0	15
13	98.5	10	30.0	30
14	13.0	1550	32.0	50
15	34.0	15	....	..
17	30.0	60	....	..
18	30.0	15	34.0	15
19	38.5	20	30.0	20
20	47.0	30	30.0	30
21	43.0	15	26.0	20
22	43.0	10	....	..
24	47.0	30	26.0	30
25	43.0	30	30.0	40
26	38.5	20	30.0	80
27	43.0	30	26.0	80
28	38.5	30	26.0	80
29	43.0	80	30.0	100
	1076.0	239	594.5	920
Average	43.0	89.7	31.4	48.4

SUMMARY: The daily values and monthly averages of the signal strengths of the Lafayette station (23,400 m.), and of Nauen (12,500 m.), and the simultaneous strengths of the atmospheric disturbances are given for March and April, 1922.

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SOME RECENT DEVELOPMENTS OF REGENERATIVE CIRCUITS*

By

Edwin H. Armstrong

(Marcellus Hartley Research Laboratory, Columbia University, New York)

It is the purpose of this paper to describe a method of amplification which is based fundamentally on regeneration, but which involves the application of a principle and the attainment of a result which it is believed is new. This new result is obtained by the extension of regeneration into a field which lies beyond that hitherto considered its theoretical limit, and the process of amplification is therefore termed *super-regeneration.*

Before proceeding with a description of this method it is in order to consider a few fundamental facts about regenerative circuits. It is well known that the effect of regeneration (that is, the supplying of energy to a circuit to reinforce the oscillations existing therein) is equivalent to introducing a negative resistance reaction in the circuit, which neutralizes positive resistance reaction, and thereby reduces the effective resistance of the circuit. There are three conceivable relations between the negative and positive resistances: namely—the negative resistance introduced may be less than the positive resistance, it may be equal to the positive resistance, or it may be greater than the positive resistance of the circuit.

We will consider what occurs in a regenerative circuit containing inductance and capacity when an alternating electromotive force of the resonant frequency is suddenly impressed for each of the three cases. In the first case (when the negative resistance is less than the positive), the free and forced oscillations have a maximum amplitude equal to the impressed electomotive force over the effective resistance, and the free oscillation has a damping determined by this effective resistance. The steady state is attained after the initial free oscillation dies out and continues until the impressed emf. is removed, when the current dies out

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in accordance with a second free oscillation. The maximum amplitude of current in this case is always finite; it reaches this maximum amplitude in a finite time, and when the impressed emf. is removed the current dies away to zero. This is the action of the circuits which are now in every-day practical use.

In the second case the negative resistance is equal to the positive resistance, and the resultant effective resistance of the circuit is therefore zero. When an emf. is suddenly impressed in this case, the current in the circuit starts to increase at a rate which is directly proportional to the impressed electromotive force and to the square root of the ratio of the capacity to the inductance of the circuit (for a given impressed frequency). If the force is impressed for an infinite time, then the current in the circuit reaches infinity. If the emf. is impressed for a finite time, then the current reaches some finite value. When the impressed emf. is removed, the current in the circuit at that instant continues indefinitely with unchanged amplitude as a free oscillation. Theoretically, this is the limiting case for regeneration; practically, it is always necessary to operate at some point slightly below this state at which the circuits have a definite resistance.

It is important to note here that altho the circuit of this case has zero resistance, oscillations will not start unless an emf. is impressed upon the circuit; furthermore, that oscillations once started continue with undiminished amplitude indefinitely. This state cannot be attained in practice, because the negative resistance furnished by the tube is dependent on the amplitude of the current and for stable operation decreases with increasing amplitude.[1]

In the third case the negative resistance introduced into the circuit is greater than the positive resistance, and the effective resistance of the circuit is therefore negative. When an emf. is impressed upon a circuit in this condition, a free and a forced oscillation are set up which have some interesting properties. The amplitude of the forced oscillation is determined by the value of the impressed emf. divided by the resultant resistance of the circuit. The free oscillation starts with an amplitude equal to the forced oscillation, and builds up to infinity regardless of whether

[1] It is very important at this point to distinguish between this purely theoretical state and the state which exists in oscillating tube circuits. In the various forms of self-heterodyne circuits a free oscillation of constant amplitude is maintained in the system and the circuit may be considered as having zero resistance, *but only for that particular amplitude of current.* An external emf. impressed on the circuit always encounters a positive resultant resistance, assuming, of course, that the existing oscillation is stable. This is due to the non-linear characteristic of the tube.

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or not the external emf. is removed. This free oscillation starts with an amplitude which is proportional to the impressed force, and this proportionality is maintained thruout any finite time interval (with constant impressed electromotive force).

It is important to note that altho the negative resistance of the circuit exceeds the positive, and the effective resistance of the circuit is negative, oscillations will not occur until some emf. is impressed. *Once an emf. is impressed, however, no matter how small it may be, the current in the circuit builds up to infinity regardless of whether or not the external emf. is removed.*

The fundamental difference between the case in which the resistance of the circuit is positive and the case in which the resistance of the circuit is negative may be summed up as follows: in the first, the forced oscillation contains the greatest amount of energy and the free oscillation is of very minor importance[2] (after a short interval of time), in the second, it is the free oscillation which contains the greatest amount of energy and the forced oscillation which is of negligible importance.

It is, of course, impossible with present-day instrumentalities to set up a system in which the negative resistance exceeds the positive without the production of oscillations in the system, since any irregularity in filament emission or impulse produced by atmospheric disturbances is sufficient to initiate an oscillation which builds up to the carrying capacity of the tube. It is, however, possible, by means of various expedients, to set up systems which avoid the production of such a paralyzing oscillation and which approximate the theoretical case in the use of a free oscillation to produce amplification.

The first use of the free oscillation in a regenerative system for the amplification of signals appears to have been made by Turner[3] in his valve relay system. Briefly, Turner prevented the regenerative circuit from producing oscillations when no signals were being received by placing a negative potential on the grid of sufficient value to hold it just below that point on the characteristic curve at which self-oscillation would start. The impressing of a small electromotive force of sufficient value would carry the potential of the grid over the "threshhold" value and a free oscillation would start which would build up to the limiting

[2] This is strictly true when dealing with continuous waves which we have been considering. It is not true in the regenerative reception of spark signals, particularly of short wave length, large damping, and low spark frequency. In this case the energy in the free oscillation exceeds the energy in the forced oscillation.

[3] British Patent, 130,408.

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value of the tube. The system was returned to its initial sensitive state by means of a relay operated by the increase in the plate current of the tube. This relay short-circuited the feed-back coil, thereby cutting off the supply of energy and permitting the potential of the grid to drop back below the "threshhold" value. As Turner explains, the device is a relay with a low limit (as distinguished from an amplifier), but it appears to be the first device in which the free oscillation set up by an impressed electromotive force produced the magnified result.

Bolitho[4] contributed an important improvement by replacing the mechanical relay of Turner which operated only upon the receipt of a signal by a valve relay which was continuously operated by independent means. Briefly, this was accomplished by connecting a second valve to the oscillating circuit of the Turner arrangement with a reversed feed-back connection and supplying the plate circuit of this second valve with alternating current. When the "threshhold" value of the first tube was overcome and a free oscillation started in the system, the reversed feed-back of the second tube comes into action and at that time when the voltage supplied to the plate is positive, damps out the free oscillation and permits the grid of the first tube to return below the "threshhold" value. This represents the second step in the utilization of the free oscillation for the production of amplification.

It is the purpose of this paper to describe a principle of operation based on the free oscillation which is quantitative and without a lower limit. This new method is based on the discovery that if a periodic variation be introduced in the relation between the negative and positive resistance of a circuit containing inductance and capacity, in such manner that the negative resistance is alternately greater and less than the positive resistance, but that the average value of resistance is positive, than the circuit will not of itself produce oscillations, but during those intervals when the negative resistance is greater than the positive will produce great amplification of an impressed emf. The free oscillations which are set up during the periods of negative resistance are directly proportional in amplitude to the amplitude of the impressed emf. The variation in the relation between the negative and positive resistance may be carried out by varying the negative resistance with respect to the positive, by varying the positive resistance with respect to the negative, or by varying both simultaneously at some frequency which is generally rela-

[4]British Patent, 156,330.

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tively low compared to the frequency of the current to be amplified.

These three methods of producing the super-regenerative state are illustrated respectively by Figures 1, 2, and 3, which figures indicate the general scheme of the system and the methods of varying the relation between the negative and positive resistance. Figure 1 shows a method of varying the negative resistance produced by the regenerative system by varying the voltage of the plate of the amplifying tube by means of a second tube, the grid of the second tube being excited by an emf. of suitable frequency.

Figure 2 illustrates a method of varying the positive resistance of the circuit with respect to the negative. This is accomplished by connecting the plate circuit of a vacuum tube in parallel to the tuned circuit of the regenerative system and exciting the grid by an emf. of suitable frequency. Figure 3 illustrates a combination of these two systems in which simultaneous varia-

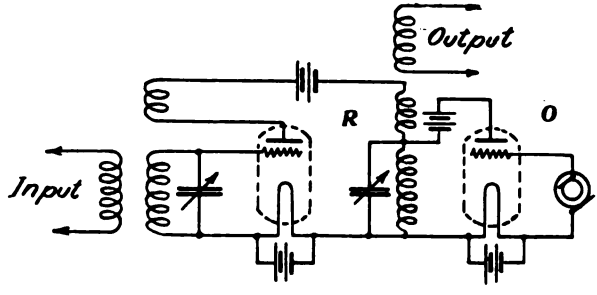

FIGURE 1

tions are produced in both the negative and positive resistances and provision made for adjusting the relative phases of these two variations.

A general idea of the phenomena occurring in these systems when an emf. is applied to the input circuit will be obtained from the diagram of Figure 4 which applies specifically to the circuit of Figure 1. This figure illustrates the principle relations existing in the system in which the positive resistance is constant and the variation is introduced into the negative resistance. It will be observed that the frequency of variation appears as a modulation of the amplified current so that the output circuit contains currents of the impressed frequency plus two side frequencies differing from the fundamental by the frequency of the variation.

Oscillograms of the essential current and voltage relations existing in the systems of the type illustrated by Figures 1 and 2

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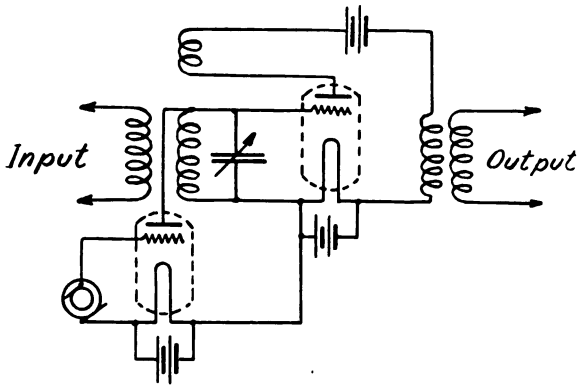

FIGURE 2

were obtained with the set up of apparatus illustrated in Figures 5 and 6, respectively. In the arrangement of Figure 6, in order to produce sufficient variation in the positive resistance of the tuned circuit, which was of large capacity and low inductance, it

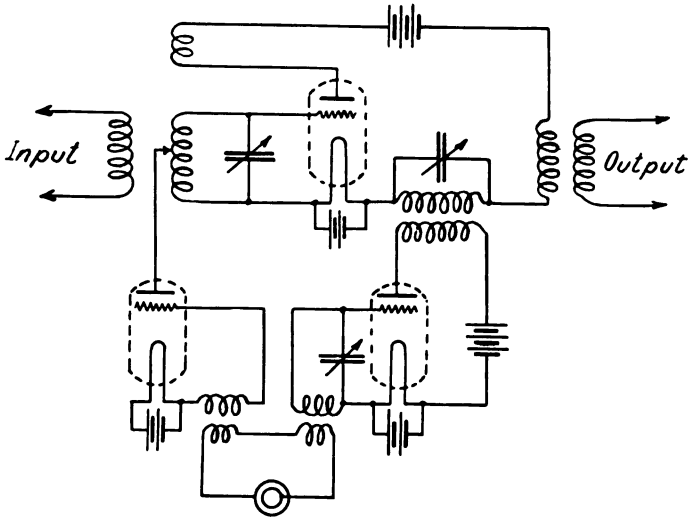

FIGURE 3

was necessary to use a two-electrode tube in series with the auxiliary emf.

Figures 7 and 8 are oscillograms respectively for a negative resistance variation and a positive resistance variation. The signaling emf. was impressed about half way along the film, the

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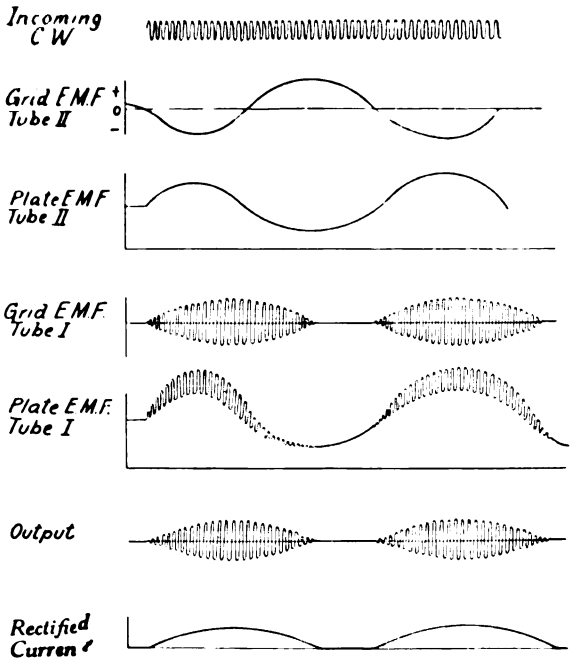

FIGURE 4
Tube I refers to R in Figure 1
Tube II refers to O in Figure 1

exact point at which the key was closed being indicated by the arrow. These oscillograms show phenomena which are in accordance with the explanations already given, but, in addition, show evidence of self excitation. It has been stated in the preceding pages of this paper that the basis of super-regeneration was the discovery that a variation in the relation between the

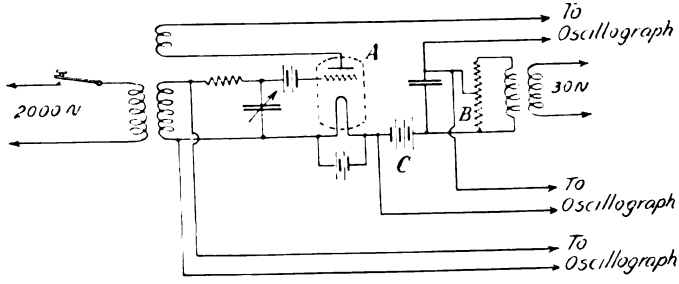

FIGURE 5
A-4 Western Electric Type L Tubes in parallel
B-AC Voltage = 100 Volts
C-DC Voltage = 160 Volts

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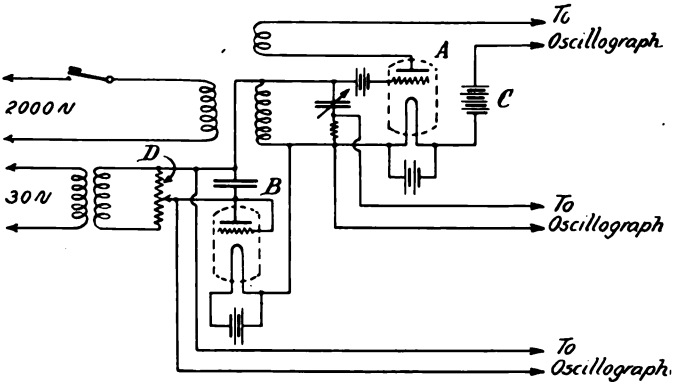

FIGURE 6

A-4 Western Electric Type L Tubes in parallel
B-1 Western Electric Type L Tubes with grid and plate in parallel
C-DC Voltage = 160 Volts
D-AC Voltage = 30 Volts

negative and positive resistances prevented a system which would normally oscillate violently from becoming self-exciting. An

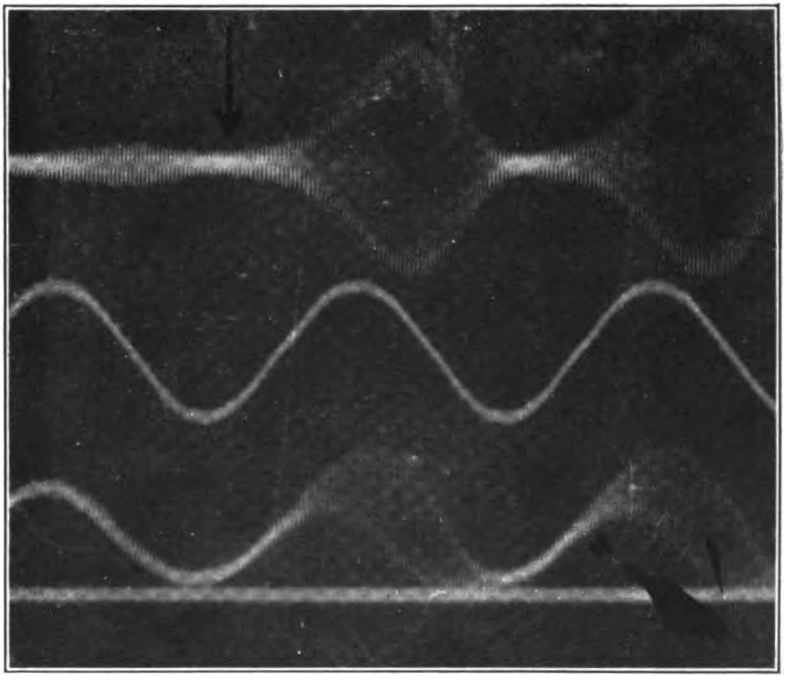

FIGURE 7

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examination of the oscillograms will show that this is not strictly true, as a free oscillation starts every time the resistance of the circuit becomes negative. It will be observed however, that this free oscillation is small compared to that produced by the signal, and therein lies the complete explanation of the operation of the system. The free oscillations produced in the system when no signaling emf. is impressed, must be initiated by some irregularity of operation of the vacuum tubes, and must start at an amplitude equal to the amplitude of this disturbance. This initial value is of infinitesimal order, and hence, in the limited time interval in which it can build up the locally excited oscilla-

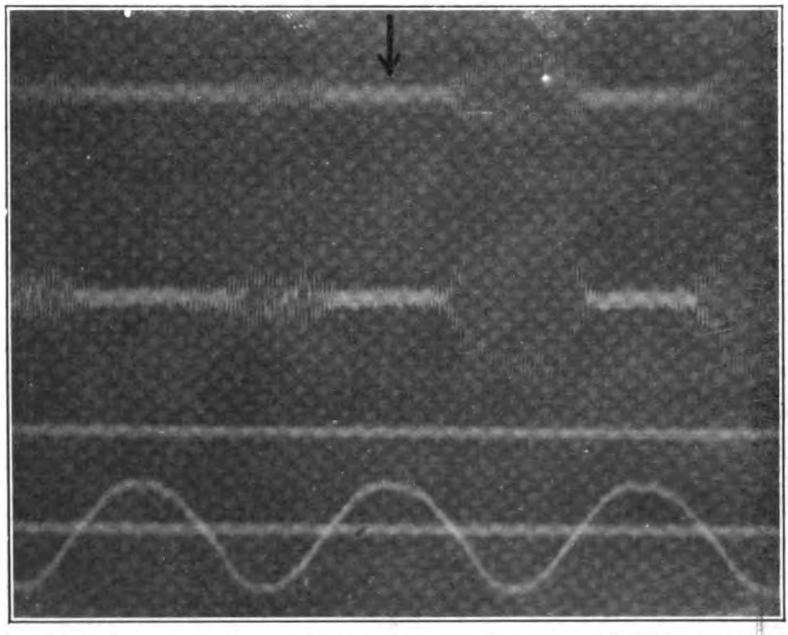

FIGURE 8

tion, never reaches an amplitude comparable to the oscillation set up by a signal of any ordinary working strength.

There is a second point of interest which is most evident from the curves of Figure 7. It will be observed that there is a decided lag in the maximum value attained by the free oscillation set up by a signal and the maximum value of plate voltage (negative resistance) of the amplifying tube. This is most evident from the plate current curve. It is a point of considerable interest, and the phenomena involved will be analyzed in a later part of the paper.

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The rate of variation in the relation between the negative and positive resistance is a matter of great importance. It may be at sub-audible, audible, or super-audible frequencies. In radio signaling, for the reception of telephony, the variation should be at a super-audible frequency. For modulated continuous wave telegraphy and spark telegraphy, to retain the tone characteristics of the signals, it must be well above audibility; for maximum amplification a lower and audible rate of variation should be used. In continuous wave telegraphy, where an audible tone is required, the variation is at an audible rate; where the operation of an indicating device is required, a sub-audible frequency may be best. The choice of frequency is a compromise, particularly in telephony, since obviously the lower the frequency the greater the amplification, and the higher the frequency the better the quality.

Some practical forms of circuits are illustrated by Figures 9, 10, and 11, which illustrate respectively the three types of variation. Figure 9 shows a method of varying the plate voltage of the amplifying tube *R* by means of the vacuum tube oscillator *O* coupled into the plate circuit. In this arrangement a third tube *D* acts as a detector. This is essential when an audible frequency is employed; when a super-audible frequency is used the telephones can be placed directly in the plate circuit of the amplifying tube.

Figure 10 shows the second case in which the variation is

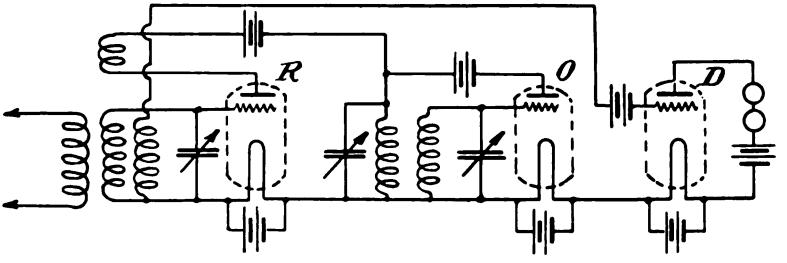

FIGURE 9

introduced into the positive resistance of the tuned circuit. This is done by means of an oscillating tube *O*, the grid circuit of which is connected thru the tuned circuit *LC* of the amplifying tube *R*. The variation in the resistance of the circuit is effected thru the variation in potential of the grid of the oscillating tube. During that half of the cycle, when the grid of the oscillating ube is positive, energy is withdrawn from the tuned circuit in

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the form of a conduction current from the grid to the filament of the oscillating tube, thereby increasing the effective resistance of the circuit. During the other half of the cycle, when the grid of the oscillating tube is negative, no conduction current can flow thru the grid circuit of the oscillating tube, and hence no resistance is introduced into the tuned circuit of the amplifying tube. In this case the amplifying tube serves also as the detector for any frequency of variation, as the tuned circuit forms a sufficiently good filter even for an audible frequency to prevent a disturbing audible tone in the telephones.

Figure 11 illustrates the case of a simultaneous variation in both positive and negative resistances. This is accomplished by providing the amplifying tube R with a second feed-back circuit L_1C_1 and L_2C_2 adjusted to oscillate at some lower frequency, thereby introducing a variation in the negative resistance thru the variation of the plate potential of the amplifier and a varia-

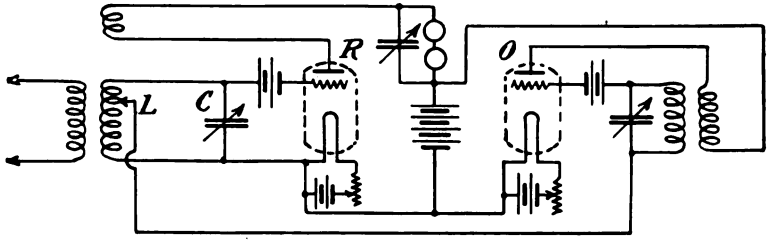

FIGURE 10

tion in the positive resistance by means of the variation of the grid of the amplifier. The proper phase relations between the negative and positive resistance are obtained by adjustment of the capacity of condensers C_1 and C_2 and the coupling between L_1 and L_2. In operation this system is very critical, and extreme care is necessary in order to obtain the super-regenerative state.

In each of the preceding cases the detecting function has been carried out either by a separate tube or by means of the amplifying tube. When a super-audible frequency of variation is employed, it is sometimes of advantage to perform the detecting function in the oscillating tube, and an arrangement for carrying this out is illustrated in Figure 12. The operation of this system is as follows: incoming signals are amplified by means of the regenerative action of the amplifier tube R and the variations of potential across the tuned wave frequency circuit LC impressed upon the grid of the oscillating tube O. These oscillations are

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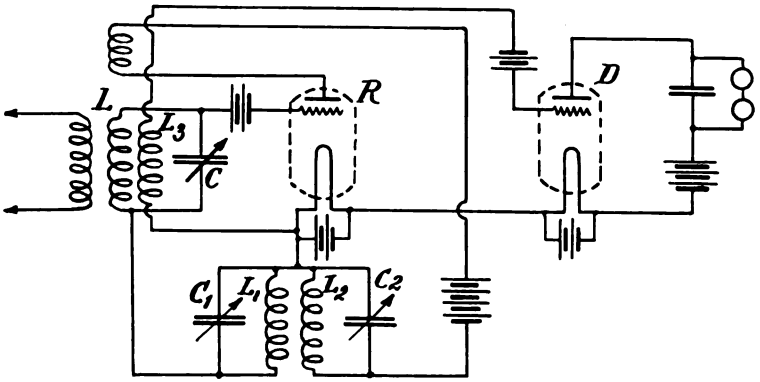

FIGURE 11

then rectified, and two frequencies are produced in the circuits of the amplifier tube. One of these frequencies corresponds to the frequency of modulation of the signaling wave. The other corresponds to the frequency of the variation and contains a modulation in amplitude corresponding to the modulation of the transmitted wave. This second frequency is then impressed upon the circuits of the oscillating tube with which it is in tune, amplified by the regenerative action of the system $L_1C_1L_2O$, and then rectified. The amplification obtainable with this form of

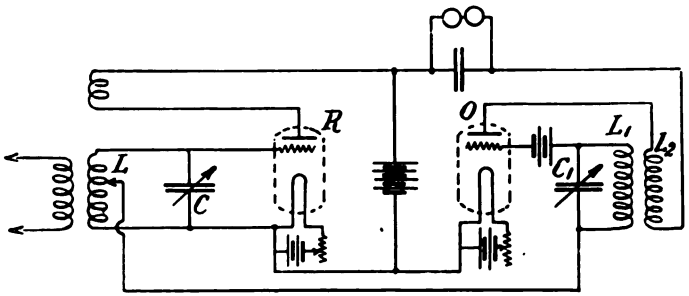

FIGURE 12

system is considerably greater than that of the single amplification circuits, but is naturally more complicated to operate.

When a super-audible variation is employed in a system such as illustrated in Figure 1, it is generally necessary to introduce a certain amount of resistance in the tuned circuit to insure the dying out of the free oscillation during the interval when the resistance of the circuit is positive. This is most effectively carried out by means of the arrangement illustrated in Figure

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13, in which a secondary coil L_1 of large inductance and high resistance is coupled to the tuned circuit LC and the energy withdrawn thereby from the oscillating circuit stepped up and applied to the grid of the tube. In the operation of this system, a curious phenomena is encountered. This is the manifestation of an inductive reaction by the plate circuit of the amplifying tube to the auxiliary frequency emf. supplied the plate circuit

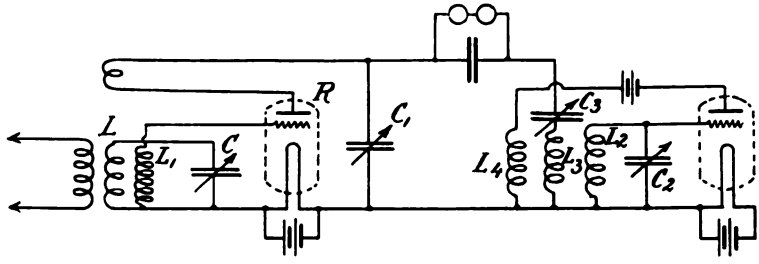

FIGURE 13

by the oscillating tube, which comes about in the following way. When the auxiliary emf. is impressed upon the plate of the amplifying tube, a current is produced in this tube in phase with the emf. across the tube. Now suppose the plate voltage is at its maximum positive value. This means that the negative resistance of the circuit is a maximum in amplitude. This in turn means that the average value of the grid is becoming more positive and the current in the plate circuit is likewise increasing. Since the free oscillation in the system will increase in amplitude as long as the resistance of the circuit is negative, it will reach its maximum amplitude after the maximum positive voltage is applied to the plate. Hence the component of current corresponding to the frequency of the variation set up in the plate circuit by the rectification of the radio frequency oscillations lags in phase behind the auxiliary emf. impressed on the plate. Hence the plate circuit of the tube manifests an inductive reaction to the auxiliary emf. It was found that this inductive reaction could be tuned out by means of the parallel condenser C_1 with a great improvement in the stability of the operation of the system and increase in the signal strength. The resonance point is pronounced, and once the other adjustments of the system have been correctly made is as readily found as any ordinary tuning adjustment.

The problem of cascade amplification with these systems is a rather involved one on account of a great number of effects which

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are not encountered in ordinary methods of cascade amplification. The principal trouble is the reaction of the second amplifying system on the first, and the difficulty of preventing it in any simple way on account of the high amplification per stage. While this difficulty is not insuperable, a simple expedient may be employed which avoids it. On account of the large values of radio frequency energy in these amplifying systems, the second harmonic is very strong in the plate circuit of the amplifying tube and is of the same order of magnitude as the fundamental if the tube is operated with a large negative voltage on the grid. Hence by arranging the second stage of a cascade system to operate at double the frequency and to amplify this harmonic, the difficulty is avoided. The general arrangement of such a system is illustrated by Figure 14, in which the positive resistance of the circuits LC and L_1C_1 of a two-stage amplifier are varied synchronously by a single oscillator. The circuit L_1C_1 in this case is tuned to the second harmonic of the circuit LC, but the combinations of circuits which may be arranged on this principle are very numerous.

One of the curious phenomena encountered with the superregenerative system is found when it is attempted to secure

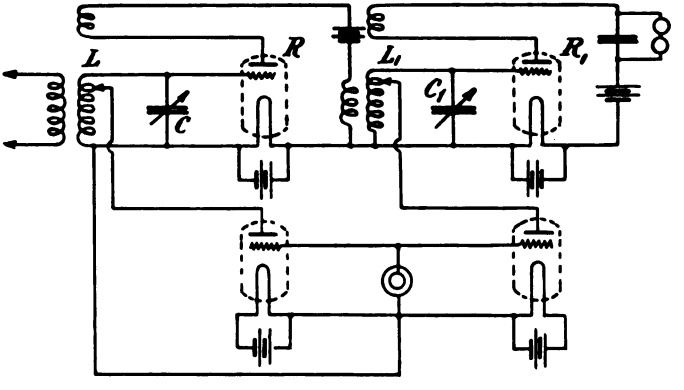

FIGURE 14

sharp tuning by the use of tuned circuits placed between the antenna and the amplifying system. The free oscillations set up in these circuits by the reaction of the amplifying system continue in these circuits during the interval when the resistance of the amplifier circuit is positive, re-excite the amplifier when the resistance becomes negative, and hence the entire system is kept in a continuous state of oscillation. The effect is most critical,

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and may be produced with most extremely weak couplings between the amplifier circuit and the second tuned circuit. The simplest solution of the difficulty is to perform the function of tuning at one frequency and amplification at another, and this is best accomplished by means of the super-heterodyne method illustrated by Figure 15. This may be adapted to work on either the sum or difference frequencies, but when the higher frequency is used, care should be taken that it is not near the second harmonic of the local heterodyning current. In the particular arrangement illustrated, *LCD* represents, together with the heterodyne, the usual agency for changing the incoming frequency, and

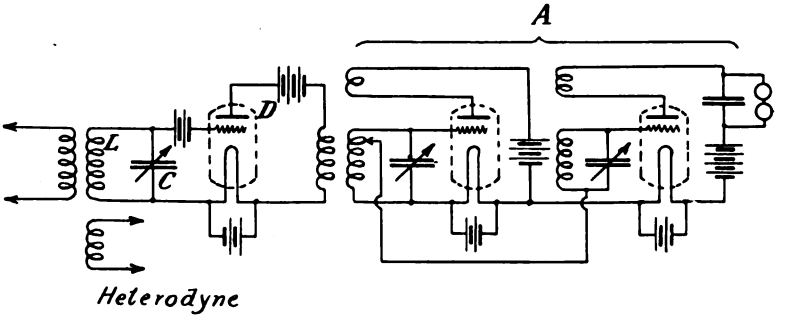

FIGURE 15

A represents the super-regenerative amplifier which may be of any suitable type.

Some of the results obtained in practice with super-regenerative systems compared to simple regenerative systems may perhaps be of interest. In general, it may be stated that the amplification which can be obtained varies with the frequency of the incoming signal and with the radio of the wave frequency to the auxiliary frequency. The higher the signaling frequency and the greater the ratio of this frequency to the auxiliary frequency, the greater the amplification. Other things being equal, it appears that the energy amplification varies as the square of the ratio of the signaling frequency to the auxiliary frequency. Hence, it follows that for telegraphic signals where an audible auxiliary frequency is used, much greater amplification can be obtained than in the case of telephony, where a super-audible auxiliary frequency must be employed. Using the arrangement of Figure 11 for a signaling frequency of five hundred thousand cycles, an energy amplification several million times greater than that obtainable with a simple self-heterodyne circuit is

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readily secured. Where a super-audible frequency is used for the reception of telephone signals, amplification of fifty thousand to one hundred thousand times energy can be obtained.

In a practical way the relative amplification of the new system with respect to the standard regenerative system for reception of telephone signals may be visualized as follows: With a signal so extremely weak that only the faintest of beat notes can be heard in the ordinary regenerative receiver, the super-regenerative receiver will give clearly understandable speech. For signals of sufficient strength to be understandable with the ordinary regenerative system with zero beat adjustment but not audible without local oscillations, the super-regenerative receiver will produce signals loud enough to be heard thruout the room.

Perhaps the most surprising characteristic of the system, apart from the amplification, is its selectivity with respect to spark interference when a super-audible frequency of variation is used. The explanation of this selectivity with respect, for example, to the ordinary regenerative receiver, lies in the periodic suppression of all free vibrations in the system. In the ordinary regenerative system spark interference approximates a form of shock excitation setting up a free vibration in the system which, because of the low damping existing therein, continues for a long period of time. An examination of the character of the oscillation set up will show that the energy existing in the free vibration after the initial impressed electromotive force is removed, is far greater than the forced vibration. In the ordinary system this free vibration may exist for a thousandth of a second or more. In the super-regenerative system this free vibration is damped out before it has proceeded more than one twenty thousandth of a second as a maximum. Hence, the interference from spark signals is greatly reduced. This phenomenon opens up a new field for the suppression of interference produced by shock excitation.

At the present time, on a three-foot loop antenna located twenty-five miles from the station WJZ at Newark, New Jersey, and a system of the type illustrated in Figure 12 with one stage of audio frequency amplification (three tubes in all) the announcements and musical selections are clearly audible five hundred yards from the receiver. With the same loop at the same distance, using the arrangement of Figure 11 without the separate detector tube, that is, with the telephones directly in the plate circuit of the amplifier tube, it is possible to operate a loud-

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speaking telephone so that the program from the Newark station is plainly heard thru a large size room. The signals with the arrangements of either Figures 11 or 12 are still heard loudly if the loop is discontinued from the receiver, the coils and wires of the receiver itself collecting sufficient energy to produce response.

While the new system does not amplify the ordinary spark signal with anything approaching its efficiency on continuous wave signals, one example of spark reception may be of interest. During the past winter an amateur spark station located at Cleveland, Ohio, and operating on a wave length of about 340 meters was received nightly at Yonkers, New York, on a three-foot (1 meter) loop and the arrangement of Figure 13 with sufficient intensity to enable the signals to be read thruout the room.

In conclusion, I wish to express my very great indebtedness to Professor L. A. Hazeltine for much valuable aid in connection with the theoretical side and to Mr. W. T. Russell for his assistance thruout the experimental side of this development.

June 2, 1922. Marcellus Hartley Research Laboratory,
Columbia University, New York.

SUMMARY: A system of circuits is described whereby the effective resistance of a regenerative circuit is periodically made positive and negative, tho predominantly positive. Such a circuit will respond to impressed electromotive forces by setting up free oscillations during the negative resistance period, which oscillations are proportional to the exciting emf. The forced oscillations produced by the exciting emf. will be comparatively small. The free oscillations caused by any normal variations in tube operation will also be small.

Means of carrying regenerative circuits thru the requisite resistance cycles are shown, and the practical operation of the system, including the case when extreme amplifications are desired, is discussed.

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RESISTANCE AND CAPACITY OF COILS AT RADIO FREQUENCIES*

By

J. H. Morecroft

(Associate Professor of Electrical Engineering, Columbia University, New York)

Contents

1. Schemes of resistance measurement
2. Variation of resistance of coils from zero frequency to 500,000 cycles. Cable and solid wire
3. Resistance of a series of cable coils at radio frequencies to show power factors normally obtainable in radio circuits
4. Resistance of tapped coils
5. Increase in resistance due to presence of neighboring coils
6. Natural period of various coils
7. Concept of internal capacity of a coil
8. Capacities of various coils of different shapes
9. Effects of spool, moisture, shellac, terminals, and so on, upon resistance and capacity of coils
10. Comparison of cable and solid wire coils at radio frequencies
11. Resistances of actual receiving sets

Schemes Used for Measuring Radio Frequency Resistance

The available schemes for measuring the resistance of radio frequency circuits have been well analyzed,[1] but there seem to be on record but few reliable determinations of the resistance of such coils as are used in radio circuits. The following results were obtained during the preparation of apparatus for another test; they seem useful enough to warrant publication even tho not as complete as the title of the paper would indicate.

The three schemes ordinarily available for measuring radio frequency resistance are the alternating current bridge, variation of resistance, and variation of reactance; these schemes, using continuous wave excitation, are so much better than any damped wave scheme that such has not been even considered. The bridge has the advantage of being a null method and has been

*Received by the Editor, February 15, 1922.

[1] "Bureau of Standards, Bulletin," number 74.

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used successfully by the writer and others[2] for frequencies as high as about 500,000 cycles a second; the bridge can be balanced at much higher frequencies, but the accuracy of the results obtained is questionable.

For frequencies of the order of a million cycles or more the resistance or reactance variation schemes are available; a substitution scheme is sometimes used, but its accuracy really depends upon one of the two other schemes. Of these schemes the resistance variation is more direct and, for the average circuit, is much more accurate than the others.

In the resistance variation scheme the circuit, the resistance of which is desired, is excited by coupling to a source of variable frequency power, Figure 1. By means of the variable condenser C the test circuit is brought into resonance with the impressed frequency, as indicated by the reading of the thermocouple ammeter, B. The non-inductive resistance R is then increased by a known amount and the new reading of B taken; by a suitable formula the resistance of the circuit can then be computed. The simplest scheme is to increase R until the current is reduced to half of its former value; this value of R is the value of the circuit resistance. If the resistance of B and C are known, the resistance of the coil L is at once obtained.

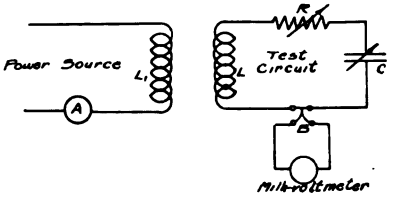

FIGURE 1

In using this method it is necessary that the voltage induced in the circuit being tested is the same for both readings; less power is drawn from the exciting source, however, after R has been increased than before and this will generally affect the current (and possibly the frequency) of the exciting source so that more voltage is induced into the test circuit after R has been increased than before. In such a case the readings of A must be noted for both readings of B, and suitable corrections applied to the calculated value of resistance.

In the experiments reported here, the power source was a 10-watt vacuum tube oscillator, the current in A being between

[2] "Note on radio frequency measurement," Carl Englund, PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS, for August, 1920.

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1 and 3 amperes. The current in the test circuit (measured by vacuum thermocouple) was less than 50 milliamperes and the resistance of the couple heater was 1.3 ohms. With the grid coupling of the power tube adjusted to a considerably tighter value than its critical value, it was found that no appreciable change occurred in the reading of A as the resistance of the test circuit was varied.

In these tests the resistance R was a dial box, built presumably free from skin effect, inductance, and so on. It was found that retuning the test circuit, after R had been changed, was not required unless the coil being measured had less than 50 microhenries inductance. With no resistance in R the coupling between L and L_1 was adjusted to give full scale reading on the millivoltmeter connected to the thermocouple; sufficient resistance was added in R to cut the deflection to nearly $\frac{1}{4}$ full scale and this value of resistance taken as circuit resistance. The millivoltmeter and thermocouple had been previously calibrated on continuous current, so that the proper reading of the millivoltmeter for $\frac{1}{2}$ full scale current was known. The calibration of several thermocouples, of the vacuum type, showed that the reading of the millivoltmeter was very closely proportional to the square of the current thru the heater; unless very accurate work is being done the quarter scale point on the millivoltmeter may be taken as half current thru the heater. It was found that resistance determinations made this way could be duplicated repeatedly to within 1 per cent. of the average.

Resistance of the Thermocouple and Condenser

Because of the high specific resistance of the heater of the thermocouple, and its very small cross-section, its resistance at radio frequency may be considered the same as its continuous current resistance; this was measured and found practically constant from zero to maximum safe current. The condenser used was the best obtainable, having a slow motion adjustment and vernier so that its setting could be duplicated to within 1/25,000th part of its full scale value. The resistance of the condenser was, however, unknown, altho evidently small, as could be told by the constructional features.

To measure the resistance of the condenser an electrically "perfect" one was constructed, meaning by "perfect" one with losses as small as it is possible to make them. The construction was mechanically very crude but electrically the condenser was very good. Two thick aluminum plates, A and B, Figure 2,

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were used for the condenser plates; they were 40 cm. (15.7 in.) long and 30 cm. (11.8 in.) wide; the lower one was fastened down to the base board, D, inside a copper pan, C-C. The upper plate was suspended by four oiled silk threads, e, e, the length of which was adjustable. The terminal for the upper plate (which was

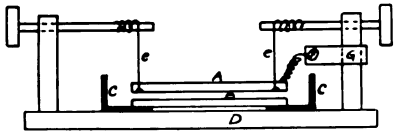

FIGURE 2

always so connected that it was the high potential plate of the condenser when being used) was a short piece of flexible cable fastened to a clip, F, which was fastened to a quartz slab, G, mounted on one of the upright posts used for supporting the upper plate. As nearly as could be determined, the condenser had no losses. It is impractical for ordinary laboratory use because of the inadequate adjustments, but it served well to measure the resistance of the mechanically good condenser, C, of Figure 1.

The arrangement of apparatus for the test was as shown in Figure 3; C_1 is the standard condenser and C_2 is the one the resistance of which is to be measured; A is a two-pole reversing switch; B is a two-way single-pole switch mounted on porcelain (to keep its losses low) which is fitted with a long insulating handle. The coil N which excites the test circuit is separated from the power supply coil M by an electrostatic shield S, made of a sheet of copper slitted vertically into strips ¼ cm. (0.1 in.) wide; these strips are insulated from each other at the top, but

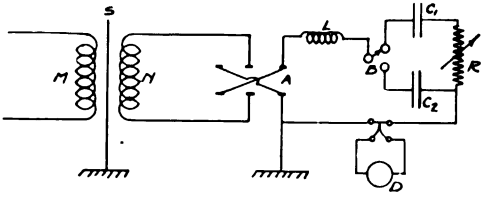

FIGURE 3

are all connected together, and to ground, at the lower ends. The reversing switch A is very necessary if accurate results are to be obtained, and it is also necessary that the high potential

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leads (those between L and C_1 and C_2) be kept short and distant from ground connections.

The manipulation requires tuning the test circuit, first using C_2, to the power supply frequency and adjusting the coupling between N and M to get a reading well up on the scale of the galvanometer D; the switch B is then thrown to connect in condenser C_1 and again the circuit is tuned. Resistance R is then varied until D reads the same as it did when C_2 was in the circuit. Presumably the value of resistance in R measures the excess of resistance of C_2 over that of C_1 which we have assumed has no loss.

As the resistance to be measured is very small, it is necessary to have very low resistance in L and in the thermocouple, if accurate results are to be expected. In this case, however, very weak coupling will be required between N and M; that is, a very low voltage will be induced into the test circuit; in the apparatus as used M consisted generally of 10 turns, 10 cm. (3.93 in.) in diameter; N had two turns, and the distance between them was sometimes as great as 30 cm. (11.8 in.). Now it may well be that there is coupling between the power circuit and test circuit other than that given by coils N and M, and, if so, this extraneous coupling will probably be different when switch B is thrown in the two positions; in this case more voltage is induced in the test circuit with one condenser than with the other, resulting in a proportionate error in the resistance determination.

This error may easily amount to 20-30 per cent. unless the wires are arranged carefully. The double throw switch generally enables one to detect an error of this kind. The voltage induced in the test circuit by the coupling of M and N has its phase reversed when A is reversed, but the extraneously induced voltage remains in the same phase it had, so that the total voltage introduced into the test circuit is altered in amount by reversing switch A. The wiring of the experiment must be so arranged that as A is reversed, no change takes place in the reading of galvanometer D. It was found necessary to place the oscillating triode set inside a copper lined box and to make the electrostatic shield S completely surround coil N before the difference in reading of D (when A was reversed) could be reduced to 1 per cent. It is interesting to note that altho the copper used in surrounding the power set was 0.05 cm. (0.02 in.) thick, all joints but the cover being soldered together and grounded, it was possible to read the wave length of the set by putting the wave meter on the top of the closed box, inside of which was

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the power set. The copper of the cover was grounded to the rest of the copper used in lining the box at two points, by flexible cable. The induction exciting the wavemeter was evidently coming right thru the copper. The reading of the wavemeter showed that the shielding was only 90 per cent. perfect; the voltage induced in the wavemeter thru the copper was 10 per cent. as much as it was with the wavemeter in the same position with the cover open. The frequency for these readings was about 500,000 cycles.

In carrying out the test indicated in Figure 3, condenser C_1 (which on account of its thread suspension does not permit of very fine adjustment) was set to give a capacity approximately equal to that of the setting of condenser C_2 for which a resistance determination was to be made. The frequency of the power set, by means of its vernier condenser, was adjusted to give resonance with the test circuit. It was found best to have the power set at least two meters (6 feet) from the test circuit; the vernier condenser was fitted with a long wooden handle so that the frequency could be adjusted while the galvanometer D was being observed.

The switch was then thrown to condenser C_2 which, by its fine adjustment, permitted tuning the test circuit accurately to the power circuit, and the coupling of N and M was changed, by means of another long handle, to give nearly full scale reading on D. Then B was thrown back to put C_1 in circuit, and sufficient resistance put in R to give the same deflection as for C_2. This test showed that condenser C_2, which was used in all subsequent tests, had extremely low resistance. With a capacity as low as 75 micro-microfarads at a wave length of 800 meters, it showed 0.5 ohm resistance. This resistance decreased rapidly with increase in capacity for fixed frequency and also decreased inversely as the frequency for a given condenser setting. In the ranges of capacity and frequency to be used later, it showed a resistance less than 0.1 ohm; as this was about the precision obtainable in most of the following tests the condenser resistance was neglected.

Using condenser C_1, which had no appreciable resistance, it was possible to get the resistance of the couple, connecting wires, and coil N, by eliminating coil L and making a resistance determination; this was of course possible only for the short wave lengths because of the low value of inductance in the circuit after L had been taken out. This resistance was less than two ohms, except

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for very short waves; by extrapolation the resistance of this part of the circuit for the longer waves was easily obtained.

The Power Set

The oscillating triode power circuit used two 5-watt tubes in parallel, and would give from 1 to 3 amperes in coil M for all frequencies between 100 meters and 4,000 meters. For wave lengths less than 100 meters, it was necessary to set up another circuit as it was practically impossible to construct a coil large enough to give 4,000 meters which, when using one part of it, would oscillate at less than 100 meters. Even tho the coil was built with 0.2 cm. (0.08 in.) air space between layers, and each layer was disconnected from every other, the different parts constitute a group of inductors and capacities which have large losses for wave lengths less than 100 meters. Coil N had two turns and coupling was varied by moving N away from M, the two remaining coaxial. A motion of 30 cm. (11.8 in.) between N and M gave sufficient change in coupling to permit using the same thermocouple and galvanometer for resistances between 3 ohms and 150 ohms.

Single Layer Solenoids. Solid Wire and Cable

The first set of data relate to the resistance of several similar coils as the frequency was varied from zero to nearly 10^6 cycles per second. The coils were single layer solenoids wound upon octagonal forms of dry wood; check tests showed that all of the resistance measured was actual wire resistance, there being negligible dielectric hysteresis and leakage in the wooden reels themselves.

The first set of results (Figure 4) show the resistance variation of four coils made of solid copper wire; the length of each coil was 10 cm. (3.93 in.) and the average diameter was 10.5 cm. (4.12 in.). The size of the wire, number of turns, and so on, of each coil is given on the curve sheet. In a single straight wire the ratio of a.c. to d.c. resistance varies nearly as the square root of the frequency,[3] and it might be supposed that the resistance of coils would vary in nearly the same manner, the rate of increase being somewhat greater in the coils because of the greater potential gradient of the magnetic field of the coil.

Inspection of Figure 4, however, shows that the variation is a peculiar one, the resistance varying rapidly at first, then less so, and finally increasing again more and more rapidly. The first rapid increase (up to about 200,000 cycles) is probably due to

[3]Cohen, "Calculation of Alternating Current Problems," page 5.

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the current shifting to the inside of the coil because in this range of frequency there occurs also a decrease in the self induction of the coil.[4] Above 200,000 cycles the resistance variation becomes a smooth curve, with no more points of inflection; this smooth curve may be extrapolated into the low frequency range and its equation be determined. Even with this smooth curve

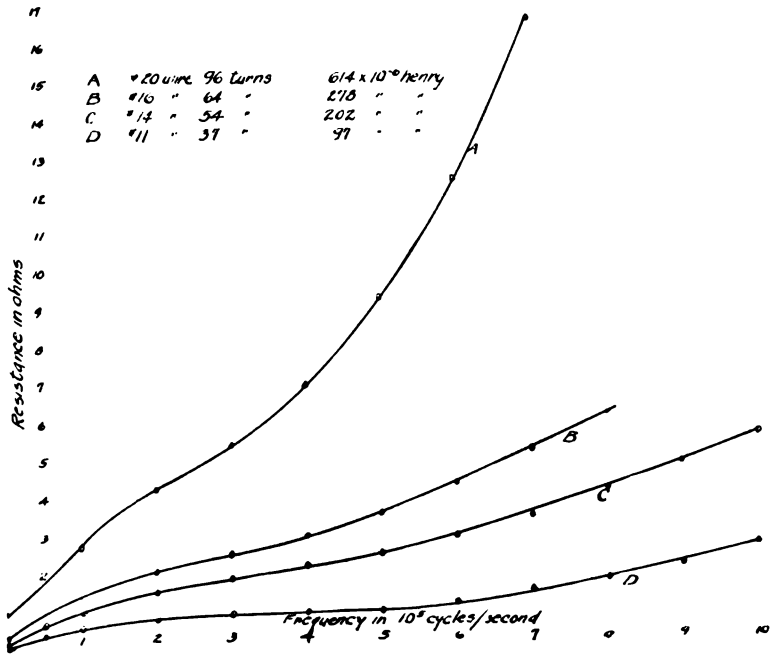

FIGURE 4

the resistance variation is not a simple function of the frequency, however, as it is with straight wires; in the lower frequency range the ratio of a.c. to d.c. resistance is proportional to a low power of the frequency, and at the higher frequencies used, the variation with frequency is nearly ten times as rapid. Undoubtedly the variation can be expressed in some complicated functions, but the solution so far has apparently not been attempted. The experimental results lead to an expression for the smooth curve of the form

$$\frac{\text{A.C. resistance}}{\text{D.C. resistance}} = Af^{b'}$$

In Figure 5 are shown the comparative resistances of three nearly similar coils, one wound with solid wire and the other two

[4]This re-distribution of the current is pictured in Morecroft "Principles of Radio Communication," page 125.

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with radio cable. Two of the coils had very nearly the same resistance for continuous current (direct current) and so serve well to show the relative advantages of cable and solid wire. The superiority of the 42/36's cable over the solid number 20 wire[5] increases rapidly up to a frequency of 200,000 cycles per second, and then decreases again, a result certainly not to be expected; it seems to be the general opinion that the superiority of the cable increases as the frequency increases. At 200,000 cycles, the solid wire has twice as much resistance as the cable, but at 800,000 cycles it has only 36 per cent. more resistance; moreover, the superiority of the cable is evidently decreasing as the frequency increases and it seems as tho at some frequency higher than was possible in this test the solid wire will be as good as the cable. Further evidence on this point is given later in this paper.

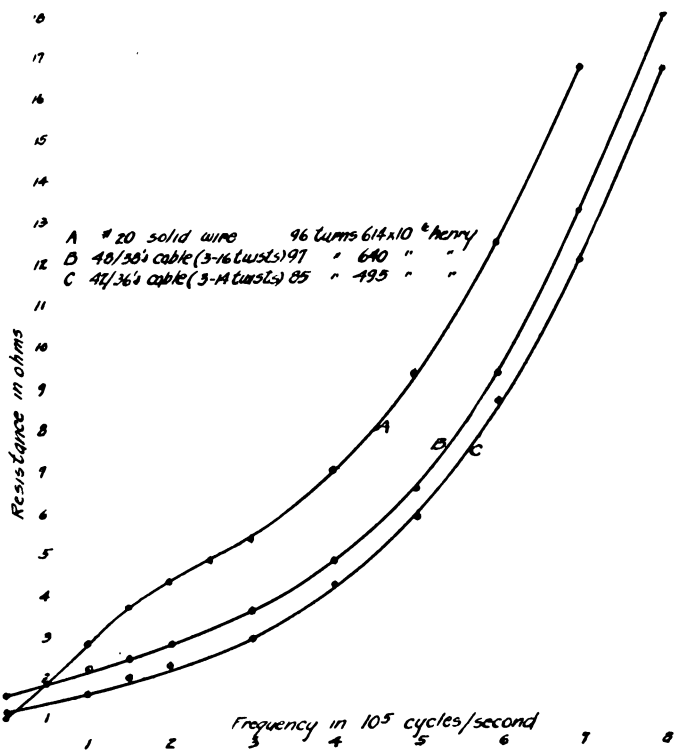
A # 20 solid wire 96 turns 614 x 10⁻⁶ henry
B 48/36's cable (3-16 twists) 97 " 640 " "
C 42/36's cable (3-14 twists) 85 " 495 " "
Resistance in ohms
Frequency in 10⁵ cycles/second

FIGURE 5

It will probably occur to the reader that the rapid increase of resistance in the upper frequency range is due to the internal

[5] 42/36 cable consists of 42 strands of number 36 wire of diameter 0.005 in. = 0.013 cm. Diameter of number 20 wire = 0.032 in. = 0.081 cm.

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capacity of the coil, as the impressed frequency approaches the natural frequency. The natural frequency of these coils, however, was nearly 3×10^6 cycles per second, so that even at an impressed frenuency of 10^6 cycles the internal capacity would produce an apparent increase in resistance of only 25 per cent.; the rapid increase in resistance at the higher frequencies shown in Figure 5 is really due to a re-distribution of the current thruout the cross section of the conductor.

Resistance of a Typical Set of Radio Coils

A complete set of cable coils, which had been made up for antenna tuning, was tested; a few of the results are shown in Figure 6. These coils were all made of 48/38's enamelled wire[6] cable (3-16 twists) double and triple layer, banked windings. The coils were all 10.5 cm. (4.12 in.) in diameter, wound on circular forms made of bitumen compound, such as is used for underground conduit. This material was later investigated for dielectric loss and was found to be sufficiently good, so that the effect of dielectric loss on the resistance of the coils measured was negligible. The coils were all thoroly dried and coated with shellac before being measured.

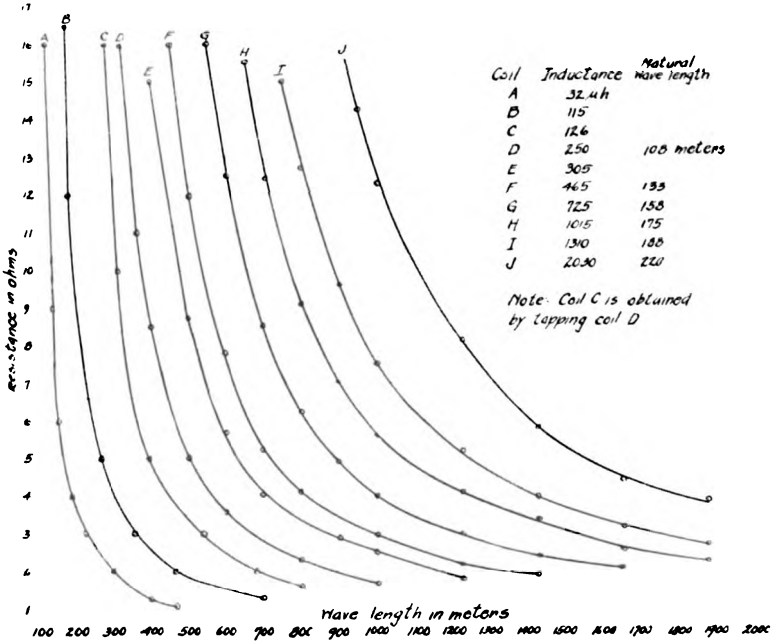

Figure 6

[6] 48/38 cable consists of 48 strands (in 3 sets of 16 wires) of number 38 wire of diameter 0.004 in. =0.010 cm.

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As the form and size of these coils are the same as used in the average radio set, they give a fair idea of what the circuit resistance of such sets should be. If a good condenser is used in the set the ratio of reactance of the coil to the total resistance in the circuit should be about as shown in Figure 7, the points of which were calculated from the curves of Figure 6, choosing for each wave length the most suitable coil. It would seem that with carefully constructed coils and condensers, at long wave lengths the reactance of the coil may be 1,000 times as much as its resistance, that is, the power factor of the coil may be as low as 0.1 per cent.

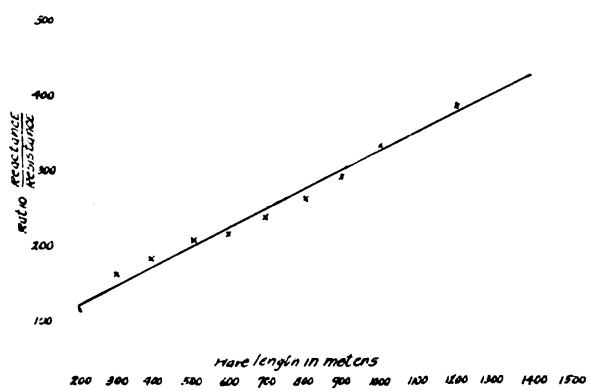

FIGURE 7

It is seen that all of the coils of Figure 6 show a very rapidly increasing resistance at the shorter wave lengths; as mentioned before it might be supposed that this increase is due to the closeness of the impressed frequency to the natural frequency of the coils; that such was not the case is evident when the natural wave lengths of the various coils, which are given on the curve sheet, are compared to the frequencies at which the resistances begin to rise rapidly.

The apparent resistance of a coil departs from its real resistance (in the neighborhood of its natural frequency) by an amount indicated by the fraction $1/(m^2-1)^2$ in which m is the ratio of the impressed frequency to the natural frequency. For example, if the impressed frequency is equal to $\frac{1}{3}$ of the natural

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frequency the effect of the internal capacity would be to give an apparent resistance 128 per cent. of the actual resistance.[7]

Resistance of a Tapped Portion of a Coil

It is well known that it is inadvisable to tap off a small portion of a large coil if less inductance is desired. Thus a coil having one millihenry might be tapped at about 1/5 of its length to get 100 microhenries as indicated at the terminals *a-b*, Figure 8. The coil is then an auto-transformer, the unused portion of the coil *b-c* being excited by the magnetic coupling with the used portion *a-b*. The potential variation of point *c* with respect to *a* will be between 5 and 10 times as much as the potential variation of point *b*; this large variation of potential will evidently cause undesired resistance and dielectric losses in the winding *b-c*, which losses will cause a proportionate increase in the resistance of that part of the coil which is being used.

A coil should never be tapped at less than ½ of its total inductance; if less than this amount of inductance is desired, a separate coil should be made. To illustrate this point, the set of curves in Figure 9 were obtained; these curves give the reactance/resistance ratio of a coil of 32 turns, tapped at 22 turns

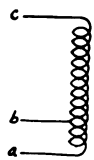

Figure 8

and on the same curve sheet is shown the reactance/resistance ratio of a coil of only 22 turns. The size of coil and kind of wire used were the same in the two cases.

Effect of Neighboring Coils

Sets are frequently put on the market with a wide wave length range, for example, 150-3,000 meters. Of course several separate coils must be used in such a set, the coil for the longest wave length having perhaps 30 times as many turns as that for the shortest. If the various coils are all mounted in the same cabinet, the larger coils, by their proximity to the smaller ones, may in-

[7]These remarks about the internal capacity of a coil follow from the ordinary conception of the internal capacity of coils; it seems to the writer, however, that the effect of the internal capacity may make itself felt at a wave length 50 per cent. greater than that predicted by the ordinary theory.

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troduce hundreds of ohms of resistance into the smaller coils, and this in spite of the fact that the larger coils are completely disconnected from the smaller ones. This effect is illustrated in Figure 10; two coils *A* and *B* were wound on the same piece of tubing, about 15 cm. (5.9 in.) apart; coil *B* had about 20 times as much inductance as had coil *A*. The resistance of coil *A*, when measured, was about as indicated in the curve in the lower

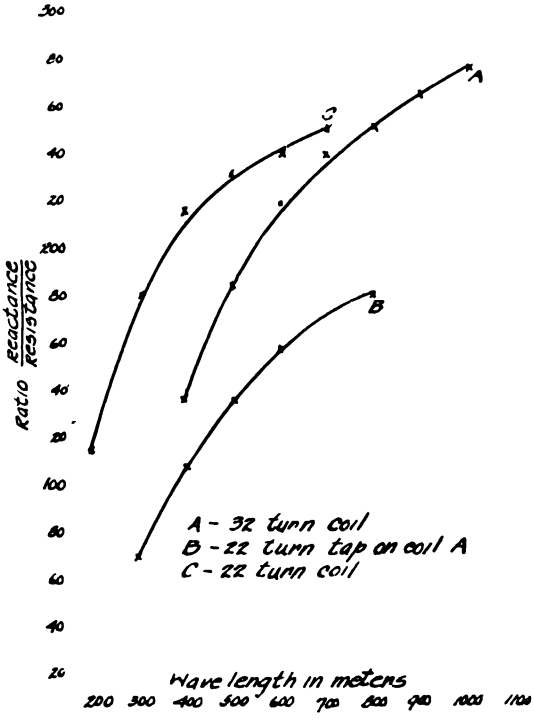

FIGURE 9

part of Figure 10. Further test showed that coil *B* had its natural wave length at 158 meters and even tho the coupling was very loose the free coil *B* introduced nearly 90 ohms resistance into coil *A* at this frequency. The writer has seen certain receiving sets which showed this effect to a marked degree; at certain frequencies the incoming signals were nearly inaudible, whereas if the signal frequency was changed slightly, the signals came in loudly.

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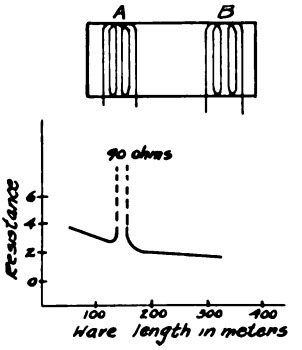

FIGURE 10

EFFECT OF TERMINAL CONNECTIONS ON RESISTANCE

A 40-turn coil, wound on a bitumen spool had its two end connections (about 20 cm. (7.9 in.) long) covered with oiled linen tube and the two ends were twisted around each other several times; no appreciable change in resistance was noted.

A similar coil was tested for resistance first with its ends free and then with them connected to two clips mounted about 2 cm. (0.79 in.) apart on a small bakelite block. The resistance with and without the terminal block are shown in Figure 11; it is seen that the resistance of a coil may be quite appreciably increased by the effect of its end connections, especially if there are many taps on the coil, brought out to a multi-point switch, mounted in such material as bakelite.

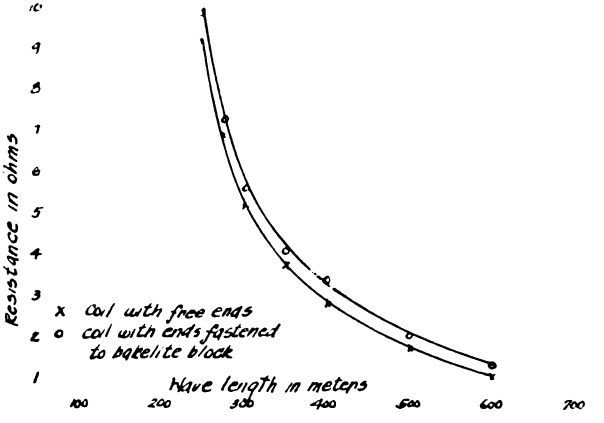

FIGURE 11

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The Natural Period of Coils

By means of a continuous wave power source the natural frequency of a coil may be measured with almost any degree of precision desired. The coil, the natural wave length of which is desired, is held on a string or stick and brought near the power oscillator. With very loose coupling between the coil and the oscillating set (less than 5 per cent. was required for most of the coils tested) the frequency of the power set is slowly varied. At a certain frequency the ammeter in the power set (either plate ammeter or high frequency hot wire meter) shows a sudden "dip." If the plate ammeter is used there may be a sudden rise instead of a dip, depending upon the type of oscillating circuit. The dip occurs when the power set and coil are tuned; reading the wave length of the power set for this adjustment gives (probably) the natural wave length of the coil.

By natural frequency is meant that frequency which sets the coil into its fundamental mode of vibration, that is, one potential node occurring at the middle and a potential loop at each free end. It may be that the coil is set into vibration at about three times, or five times, this frequency. The writer has found it very convenient to test for this condition by use of a small glass tube filled with neon at low pressure (such as are sold for automobile ignition testers). As the tube is moved down the length of the coil the potential nodes and loops are easily located.

In Table 1 are given the natural wave lengths of several coils tested in this fashion; the coils were of various shapes and sizes and wound on different kinds of spools. It will be seen that for the single layer coils of a given size and form the natural wave length varies nearly proportionately to the number of turns, that is, proportional to the square root of the inductance of the coil. For multi-layer, banked winding coils, the natural frequencies are much lower than for a single-layer coil of the same inductance.

Internal Capacity of Coils

Every part of a coil acts in conjunction with every other part to set up an electric field in and around the coil when excited, thus giving what is called the internal capacity of the coil. It is generally assumed that the internal capacity is constant, independent of the frequency; upon this assumption its magnitude is found from the measured natural wave length and the inductance of the coil measured at low frequency. Recently a note[8] has

[8] "Distributed Capacity of Coils," G. Breit, "Physical Review," August, 1921.

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Table 1

	diameter in cms	length in cms	no of turns	L in 10^{-6} henries	λ_0 in meters	C_0 in 10^{-12} farads
single layer solenoids on bitumen spools	11.7	2.3	20	79	37	5.15
	11.7	4.8	40	200	60	4.70
	11.7	7.5	60	374	78	4.44
	11.7	17.8	141	1140	122	3.6
this coil fitted with multi-point switch on paper spool	11.9	3.3	30	144	53	5.5
	12.	42.3	931	26000	625	4.2
	11.7	7.4	126	214	213	6.0
	14.7	17.6	296	7560	370	5.1
single layer solenoids on wood spools	10.5	10	361	8490	388	5.0
	10.5	10	290	5540	323	5.30
	10.5	10	130	1290	153	5.12
	10.5	10	96	614	104	5.01
	10.5	10	64	278	69	4.83
	10.5	10	41	120	49	5.60
	10.5	10	37	97.5	44	5.60
three layer banked windings on bitumen spools	11.4	1.5	36	205	108	16.0
	11.4	2.1	52	465	133	13.3
	11.4	2.7	68	725	158	9.7
	11.4	3.4	84	1015	175	8.5
	11.4	4.2	100	1310	188	7.6
	11.4	5.7	132	2030	225	7.0
	11.4	7.3	169	2880	263	6.8
	11.4	9.8	232	4220	297	5.9

appeared, showing how to calculate this internal capacity. For short single-layer solenoids, surrounded by air and free at both ends, the theory yields a capacity in micro-microfarads equal to $0.44r$, where r is the radius of the coil, in cm. In Table 1 are given the capacities of the various coils calculated from the above formula as well as the values determined from the measured natural wave length and known inductance of the coils. The agreement is evidently not good; in trying to find the reason for this discrepancy the effect of various factors entering into the coil construction was noted.

Effect of Moisture, Shellac, Spool, and so on, Upon Resistance and Capacity of Coils

It was noticed during the tests that the resistance of a coil made of cotton or silk insulated wire, not covered with varnish

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or shellac, varied as much as 30 per cent. on different days, and by check tests it was concluded that this was due to internal leakage thru moist insulation; by heating the coil for an hour or so the resistance always returned to its proper low value, and if the coil was coated with shellac while hot and dry, and then thoroly dried out, the resistance was constant from day to day. No appreciable effect of moisture on the natural period of the coil could be determined. To find the effect of spool and shellac on the natural period, various coils were built of exactly the same winding data (11.8 cm. (4.65 in.) diameter, 4.8 cm. (1.89 in.) long, 40 turns). One was wound on thin paper tube, without shellac, and was measured for natural wave length and found to give 49 meters; when coated with shellac and dried it gave 51 meters. The same winding on a bitumen spool, thoroly impregnated with shellac, gave for λ_o (natural wave length) 58 meters. In these tests the ends of the winding were about 8 cm. (3.15 in.) long. In another coil with 15 cm. (5.9 in.) ends left free the value of λ_o was 52 meters; when the 15 cm. (3.9 in.) ends bent near together so that for 10 cm. (3.9 in.) they were parallel, 1 cm. apart, λ_o was found to be 56 meters.

The magnitude of the effect of the end connections on the natural wave length is well shown by the behavior of a coil 17.7 cm. (6.97 in.) long, 7.5 cm. (2.88 in.) diameter, on which both terminals of the winding were fastened to clips mounted on a wooden block fitted in one end of the spool. This arrangement of terminals is indicated in Figure 12; one end of the winding ran from end to end of the coil thru the inside of the spool. The value of λ_o for this coil was found to be 117 meters; removing the clips to which the ends of the winding were connected, reduced λ_o to 93 meters; arranging the wire that ran thru the inside of the spool as nearly central as possible reduced λ_o to 86 meters. Pulling out the long end so that the two ends of the winding were on opposite ends of the spool reduced λ_o to 71 meters. By this re-arrangement of end connections the internal capacity of the coil had been reduced from 13.7 micro-microfarads to 5.05 micro-microfarads.

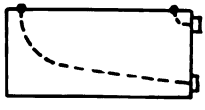

FIGURE 12

All of these internal capacities are much larger than theory (by Breit) would indicate, and evidently end connections,

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shellac, spool, thickness of insulation, and so on, have appreciable effects on the internal capacity, making it generally about twice as much as the theoretical value. In only one coil did the measured internal capacity approach the theoretical value; this one was wound on paper just thick enough to support the wire, the insulation on the wire was thicker than ordinary, the ends were cut off close to the coil. In this case the measured internal capacity was 2.55 $\mu\mu$f, whereas the theoretical value was 2.4 $\mu\mu$f.

From Table 1 it will be seen that the capacity of banked winding coils is very much greater than for single-layer solenoids, and also that the capacity varies greatly with the length of the coil, becoming smaller as the coil increases in length.[9] The large decrease in internal capacity can be readily explained when the distribution of electric field inside the coil is examined. This is indicated in Figure 13; *a* shows one side of a short single-layer solenoid and *b* shows one side of a three-layer banked winding. The electric field (which determines the internal capacity) may be divided roughly into two parts:—that close inside the winding, and that completely outside the winding. The capacity of the coil insofar as it is determined by the outside field, will not vary much with coil length, but that inside the coil, where the turns come close together, will vary inversely as the length of the coil. In a multi-layer coil, the inside capacity constitutes a much greater part of the total capacity than it does in the single-layer coil, and so we may expect the capacity of multi-layer

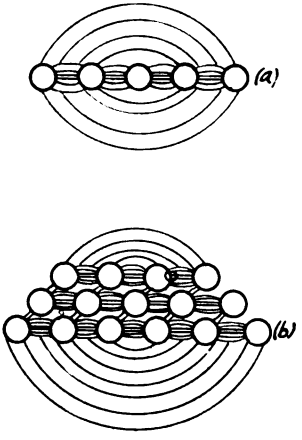

FIGURE 13

[9]In a recent editorial ("Radio Review," December, 1921), it has been stated that experiment shows the capacity of coils to be independent of length; the results given here seem to show that such is not the case.

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coils to decrease with increase of length to a greater extent than it decreases for the single-layer coil.

This is seen to be the case in the results of Table 1; for single-layer coils of constant diameter the capacity decreased to about 70 per cent. the value it had for the shortest coil as the length was increased 8 times, whereas in the 3-layer coils the capacity decreased to about ⅓ its value with the same change in coil length.

Basis of Calculation of Internal Capacity of Coils

As noted previously, the foregoing values of capacity have been calculated on the assumption usually made that the capacity stays constant and that the inductance of the coil is the same at low frequency as it is at the natural frequency of the coil. It is also assumed that when a coil oscillates at its natural frequency, the voltage and current distribution along the coil are sinusoidal.[10] It seems to the writer that neither of these assumptions is justified when one gets a mental picture of the electric and magnetic fields as they exist at low frequency and at very high frequency.

The inductance or capacity of a circuit in which the current and potential distributions are non-uniform can be conceived most readily from the standpoint of the energy in the respective fields. Thus the co-efficient of self-induction of a circuit is equal to twice the magnetic energy divided by the square of the current in the circuit. When the current varies in the different parts of the circuit, the value of current to be used in calculating L becomes more or less indeterminate; it seems reasonable, however, to use the maximum value of current occurring in the circuit. (In case the minimum value were used for a coil oscillating at its natural frequency, the value of L obtained would be infinite).

From this viewpoint, it is evident that the L of a coil changes very much from low to high frequency; in Figure 14 an attempt is made to show this. In Figure 14 *a* the field distribution of the solenoid is shown for uniform current thruout the coil, as is the case for low frequency and in *b* is shown a comparative field distribution for a distribution of current such as occurs when the coil is oscillating at its natural period, the current in the center turns of the coil having the same value as that occurring thruout the whole coil for the case shown in *a*. The energy in the magnetic field for case *b* is only about ½ as much as for case *a*, so that we may say that the L of the coil is only ½ as much in one case as in the other. As the current distribution of the coil changes with

[10]Editorial, "Radio Review," December, 1921, and other articles.

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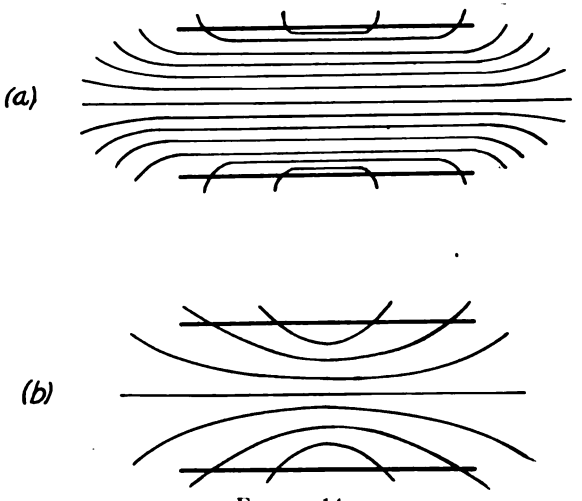

FIGURE 14

frequency, so must the electric field change its configuration, and hence a change in capacity is brought about.

The reason for assuming a sinusoidal distribution of current and potential is not evident. If a conductor having uniformly distributed inductance and capacity is oscillating at its natural period, the current and potential distribution are nearly sinusoidal, but in the case of the solenoid of appreciable length the inductance per unit length is nearly twice as much at the center of the coil as it is at the ends; the capacity of the coil per unit length is also greater at the center than at the ends of the coil. Such being the case the natural oscillation of the coil cannot be sinusoidal with respect to space altho it is so with respect to time.

COMPARATIVE MERITS OF CABLE AND SOLID WIRE

It has been long appreciated that to keep the resistance of wire low at high frequencies, it must be so built that the current is forced to divide equally between the various elements of cross-section. This is accomplished by constructing the wire of a large number of small wires, each insulated, and so interwoven therein that each individual strand is equally on the inside and outside of the cable. This was originally done by braiding together the various small wires, but a much simpler method is to make the cable of several smaller cables, each of which is made by twisting together several of the small insulated wires. This construction accomplishes practically the same thing as braiding.

But little experimental material has been given, showing how solid wire and cable compare at various frequencies. The follow-

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ing results show that a cable is preferable to a solid wire of the same diameter (that is, laying the same number of wires per cm.) in the ordinary range of radio frequencies, having about one-half the resistance of the solid wire for wave lengths about 1,000 meters; as the frequency increases, however, the superiority of the cable becomes less and rapidly disappears for wave lengths less than 300 meters; at frequencies higher than this, the solid wire is actually better than the cable. This effect is indicated in the curves of Figure 5; to bring it out more clearly several sets of coils were made and tested, there being in each set some cable coils and some of solid wire.

As mentioned before in comparing resistance at high frequencies, the internal capacity may play an important role and lead to incorrect conclusions; to eliminate the possibility of this effect nullifying the comparative value of the data of the various coils, solid wire and cables were used which wound the same number per cm., this making the capacity effects nearly the same for all coils. All coils had the same diameter, 11.8 cm. (4.65 in.); the lengths varied with the number of turns in the coil.

For single-layer coils four sets were measured having 10, 20, 40, and 60 turns each; these coils are typical of those used in short wave receiving. In each set the *A* coils were of solid wire (number 20 double cotton covered); *B* coils were braided (32 strands of number 36 enamelled wire); *C* coils were twisted cable (three cables twisted together, each consisting of 16 number 38 enamelled wires, twisted together); *D* coils were twisted (three cables twisted together each consisting of 40 number 40 enamelled wires twisted together).[11] All of these coils were wound on bitumen spools; coil *E* was wound on very thin paper tubing, coated with shellac. Three sets of banked winding coils were also tried to see if the conclusions reached for the single-layer coils could be applied to multi-layer coils.

All resistance values together with dimensions and construction of coils are given in Figures 15-18. It will be noticed that altho the cable coils have a continuous current (d.c.) resistance nearly twice as much as the solid wire, thruout most of the frequency range tested their resistance is only about one-half as much as the solid wire, showing that the stranding has made the cross-section four times as effective in one case as in the other.

[11]Diameter of number 20 wire =0.032 in. =0.082 cm.
Diameter of number 36 wire =0.005 in. =0.013 cm.
Diameter of number 38 wire =0.004 in. =0.010 cm.
Diameter of number 40 wire =0.003 in. =0.008 cm.

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For wave lengths less than 400 meters the cable resistance increases more rapidly than the solid wire, and for wave lengths less than about 250 meters the solid wire has less resistance than the cable.

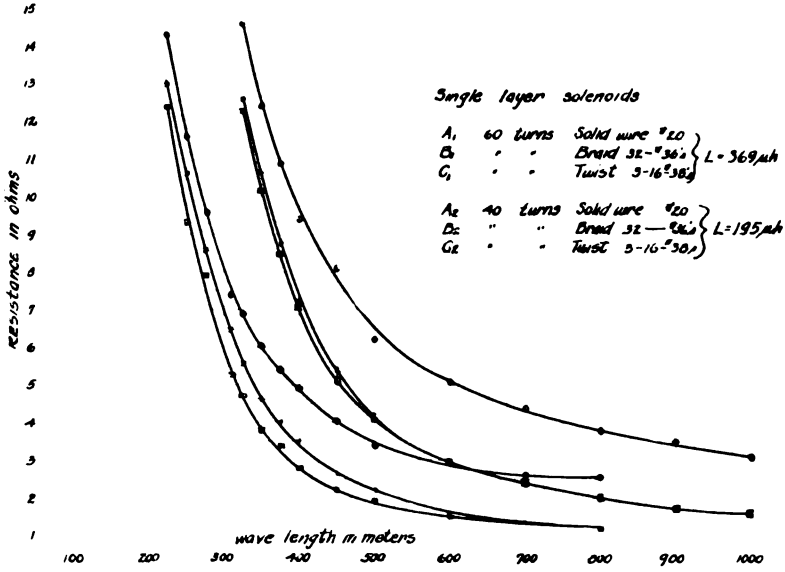

FIGURE 15

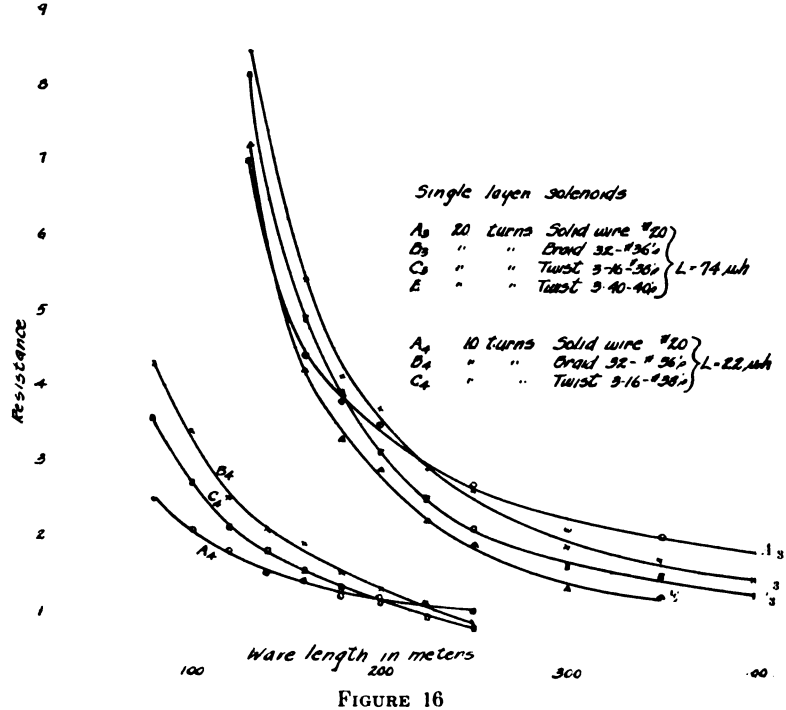

FIGURE 16

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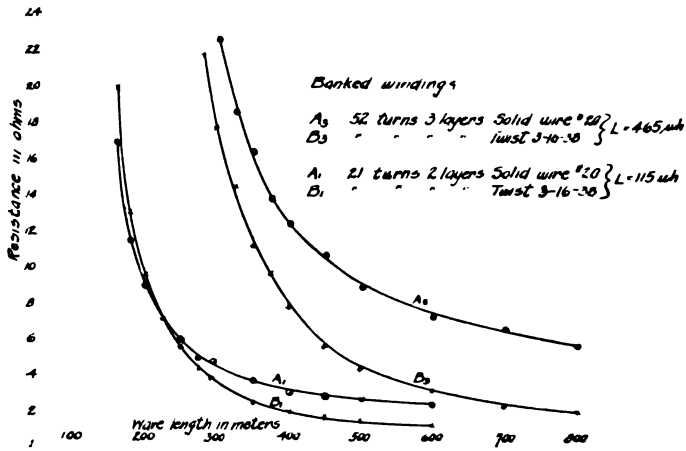
Banked windings
A3 52 turns 3 layers Solid wire #20 } L = 465 μh
B3 " " " " Twist 3-16-36 }
A1 21 turns 2 layers Solid wire #20 } L = 115 μh
B1 " " " " Twist 3-16-36 }
Resistance in ohms
Wave length in meters
A3
B3
A1
B1

FIGURE 17

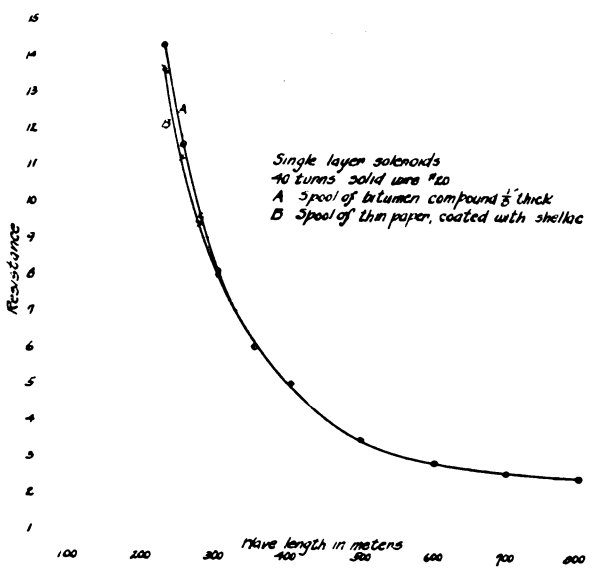

FIGURE 18

To find the effect of possible losses in the bitumen spools, a pair of coils of exactly the same winding data, one on a bitumen spool of 0.3 cm. (0.12 in.) thick and the other on a very thin paper tube, were compared for resistance; the results, given in Figure 18, show that the spool has a nearly negligible effect on the coil resistance.

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From all the results given, including those of Figure 5, it is evident that but little advantage is to be gained in using cable in ordinary receiving sets designed for wave lengths of 400 meters or less, unless the component wires are much finer than those used in these tests, and even then the superiority of the cable is much less than would be expected. Curve *E* of Figure 16, for the coils made up of number 40 wires, shows itself better than the solid wire for wave lengths greater than 150 meters, but it must be noticed, in comparing its behavior with that of the other cable coils, that it had considerably greater cross section of copper.

It is quite likely that the reason for the peculiar change in the comparative merits of the solid wire and cable is due to the dielectric losses in the enamel of the strands of the cable. In Figure 19 are illustrated two strands of a cable, each weaving in and out from the center of the cable to the outside. The two

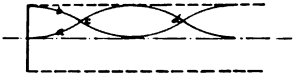

FIGURE 19

strands are soldered together at the end of the cable and hence must have the same potential at this point. Where they cross at *c*, however, they do not have the same potential, because the *IX* drop in filament *a* has been greater than that in filament *b* due to the greater flux surrounding *a*, this excess flux being that inside the cable. The enamel, at the point of crossing of the strands, will be subjected to high frequency dielectric loss and further, at very high frequency the current will not divide equally between the strands but will travel more thru the outside strands, that is, at points of crossing, as at *c* and *d*, current will tend to leave one filament and go into another, always leaving that filament which is going towards the inside of the cable for that one going toward the outside. At extremely high frequency the inside of a cable will carry but little of the current, even tho the individual strands are perfectly insulated from one another; due to the condenser action at the points of crossing, the current will always pass to the outside strands.

The dielectric loss at each crossing will be proportional to the square of the potential difference of the two strands at the crossing point; for a given frequency this will be proportional to the distance between crossings. As the number of crossings

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varies inversely with the distance between them, the total internal loss will vary directly with the distance between crossings.

At high frequencies the loss tends to increase with the square of the frequency, because of the increasing difference in the IX drop in the inner and outer filaments. In a twisted cable the potential gradients occurring in the enamel, due to this cause, are likely to be not as great as in a braided cable, so that a twisted cable, altho theoretically inferior to a braided one, may actually show lower resistance at high frequency.

If many ends are to be made and soldered on radio cable coils, much time may be consumed in cleaning each individual strand, as each must be cleaned if the resistance of the cable is to be kept low. The writer has found that a concentrated solution of potassium bichromate in concentrated sulphuric acid, when brought near its boiling point, removes the enamel in a few seconds and leaves the ends in fine condition for soldering. The end should be dipped in a soda solution, after the enamel has been dissolved, to prevent further action by the adhering acid.

Resistance of Receiving Sets

From the curves given in this paper, a reasonable resistance for a receiving set, at any wave length, may easily be obtained. Thus a small antenna, of capacity 0.0003 microfarad, to receive a 300 meter wave length, requires an inductance of 84 microhenries and for 600 meters it requires 336 microhenries. The resistance for 300 meters should be about 3.5 ohms, and for 600 meters about 6.3 ohms. These values are obtained from the curves of Figure 5, by interpolation. If the antenna had the more likely value of 0.0006 microfarad, the required resistances would be 2.3 ohms for 300 meters and 2.5 ohms for 600 meters.

A first-class commercial receiving set was measured to see what values of resistance were introduced into the antenna circuit for various adjustments and wave lengths; the results are given in Figure 20. With an antenna capacity of 0.0001 microfarad, the resistance of the circuit in the receiving set, from antenna post to ground post, varies from 52 ohms to 45 ohms as the received wave length varies from 250 to 600 meters. If the receiving antenna has a capacity of 0.0008 microfarads, the set, when adjusted to receive 250 meters, has a resistance of 24 ohms, and if adjustment is changed to receive 600 meters, the resistance is 15 ohms.

Other receiving sets were tested, with the same results; the resistance of the average set with coils mounted in a cabinet,

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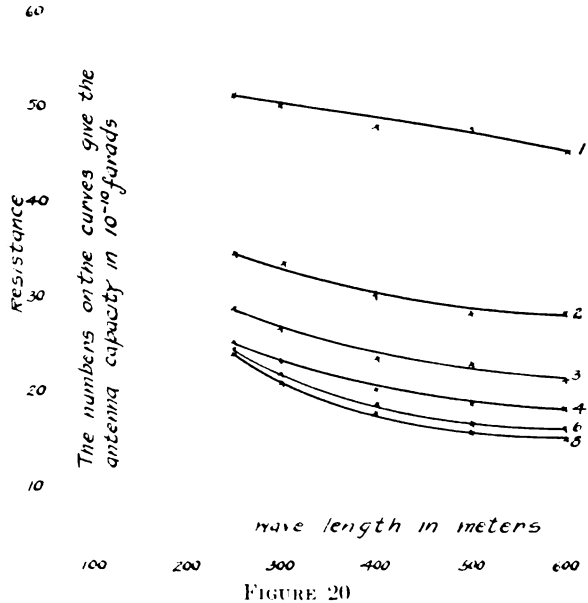

FIGURE 20

attached to multi-point switches, condensers, variometers, and so on, is from five to ten times as much as is actually required by a single, untapped, coil of the right inductance for tuning. The increase in resistance over the requisite amount is the price paid for ease of adjustment and flexibility of operation.

SUMMARY: The various practical methods of determining the resistance of coils at radio frequencies are described, and their conditions of maximum usefulness given.

The resistances of various forms of coils on different mountings are determined at various frequencies, and the laws of variation of resistance with frequency are considered. Measurements are also made of the internal capacity of coils at radio frequencies, and the physics of this capacity is investigated.

The effects on its resistance and capacity of various methods of terminating the coil, mounting it, and varnishing it are experimentally investigated. Finally, solid wire and stranded cable are compared at various frequencies; and numerical data are given on the possible resistances obtainable in actual receiving sets.

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DISCUSSION

G. Breit (by letter): Professor Morecroft considers my calculations on the distributed capacity of coils and finds them inapplicable in his work. In particular under "Effect of Moisture, Shellac, Spool, and so on, Upon Resistance and Capacity of Coils," just after Figure 12 we find the paragraph: "All of these internal capacities are much larger than theory (by Breit) would indicate, and evidently end connections, shellac, spool, thickness of insulation, and so on, have appreciable effects on the internal capacity, making it generally about twice as much as the theoretical value. In . . . coil. In this case the measured internal capacity was 2.55 $\mu\mu$f, whereas the theoretical value was 2.4 $\mu\mu$f."

I quite agree with Professor Morecroft that the leads have an appreciable effect, and that the other influences cited may be also marked. The most essential factors, however, have been investigated in previous work, as I shall proceed to show.

The effect of the dielectric constant of the spool or insulation is considered in my formulas (22), (27). The capacity according to these formulas is proportional to the dielectric constant—K. If K is not a constant, a mean value must be used. This value becomes unity only if the space occupied by the spool and insulation is negligible. This effect has been demonstrated by Drude (See P. Drude, "Annalen der Physik, 9, 1902, pages 293-339). On pages 302-307, we find the verification of the effect of the core, and on pages 308-310, the effect of the insulation is discussed.

The effect of the leads is mentioned in my paper on page 669, line 1. ("The formulas . . . are . . . in agreement with experiment if capacity of leads is taken into account and the effect of condenser shields is made negligible.") The leads may be considered a part of the condenser with as much right as a part of the coil. For this reason I preferred treating the leads separately.

As a matter of nomenclature, it does not appear to me correct to call the capacity of the leads and clips as part of the *internal* capacity as Professor Morecroft does.

The lead effects discussed in the paragraph just preceding Professor Morecroft's Figure 12 are of the same kind as the effects of condenser shields which have been warned against on my page 669, line 21. In my measurements I avoided bringing the leads close to any part of the coil except the part to which the particular lead is connected.

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Professor Morecroft's experiment demonstrating the effect of shellac is open to criticism because paper tubes warp when coated with shellac and wires are frequently shifted in the act of coating. Granting the absence of these errors, the change from 49 meters to 51 meters would amount to 8.2 per cent in the capacity, which is not very much for a capacity of 2.5 $\mu\mu$f. If a larger coil were painted with a coat of shellac of the same thickness, the percentage of the effect would be smaller.

So far as the effect of length on the capacity of multi-layer coils is concerned, it is of interest to recall the results of Pietz (W. Pietz—"Ueber die Kapazität von Spulen," "Annalen der Physik," 41, page 543, 1913. Especially pages 559 and 566). It appears that Pietz found an increase in the capacity with length instead of a decrease as Professor Morecroft does.

Professor Morecroft's experiments as to the relative advantages of stranded and solid wire are in agreement with the measurements of Lindemann and the considerations of M. Wien, cited by Lindemann. (See R. Lindemann, "Berichte der Deutschen Physikalischen Gesellschaft," 1909, page 682 and, in particular, page 696 and Figure 4) as well as the theoretical work of Butterworth ("Phil. Trans. Roy. Soc.," A596, volume 222, pages 57-100), and Howe ("Roy. Soc. Proc.," A, volume 93, page 468, 1917), which explains the general effects observed.

The displacement currents between strands which are considered by Professor Morecroft could not be pronounced in the experiments of Lindemann, for if they were, the increase in resistance would not be proportional to the square of the frequency.

National Research Fellow, U. S. A.
April 24, 1922. The University, Leyden, Holland.

J. H. Morecroft (by letter): I am in agreement with Mr. Breit in practically all his comments on my paper on "The Resistance and Capacity of Coils at Radio Frequencies." The paper pretends to be but a slight contribution of experimental results to a field which is extremely bare; the fact that the only references given by Breit are to German periodicals is sufficient evidence on this point, and he must remember that such matter is not available to the average American engineer.

Instead of endeavoring to disprove Breit's formula, as one might judge from his comments, I really did my best to prove it, and my results show that his formula is correct (within the experimental error of my work) when the extraneous effects are eliminated. The shellaced coil, to which he makes allusion, was meas-

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ured for inductance before and after coating with the shellac, and as no appreciable change was observable, it is reasonable to assume that no displacements, such as he infers, occurred. The fact that my results show internal capacity decreasing with length of coil, that Howe assumes the internal capacity independent of length, and that one of Breit's references found it to increase with length, is further evidence that there is still room for the publication of accurate experimental results in this field; this fact was further evidenced by the discussion which followed the presentation of the paper.

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DIGESTS OF UNITED STATES PATENTS RELATING TO RADIO TELEGRAPHY AND TELEPHONY*

ISSUED MAY 2, 1922–JUNE 20, 1922

BY

JOHN B. BRADY

(PATENT LAWYER, OURAY BUILDING, WASHINGTON, D. C.)

1,414,629—M. M. Dolmage, filed July 15, 1918, issued May, 2, 1922.

RADIO DUPLEX SIGNALING SYSTEM, wherein the transmitting apparatus is normally connected with the antenna. An auxiliary current is provided and a second circuit arranged for balancing the transmitting current circuit on receiving signals. The receiving apparatus is normally connected to the antenna system. A control relay is placed in the auxiliary circuit and arranged to render the receiving apparatus inoperative when the system is used for transmission whereby periods of transmission or reception can take place without manual operation of switches.

1,415,179—E. T. Jones, filed July 21, 1920, issued May 9, 1922

RADIO CONTROLLING DEVICE, for transferring the connections of an antenna system from transmitting to receiving apparatus or vice versa. An electrical switch is described having a central shaft and blades extending on opposite sides of the shaft. The shaft may be rotated by a large knob at one end hereof to move the blades into contacts on either side of the support upon which the shaft is mounted. The switch may be utilized with a broadcast receiver to cut in the filament circuits of the electron tubes simultaneously with the connection of the antenna to the receiving apparatus, while on reverse motion of the switch the filament circuit may be broken and the antenna shorted to ground for protection against lightning.

1,415,220—H. F. Causebrook, filed June 18, 1921, issued May 9, 1922.

ELECTRICAL CONDENSER, comprising a continuous strip of

*Received by the Editor, July 10, 1922.

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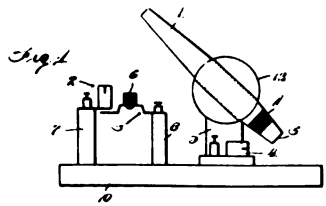
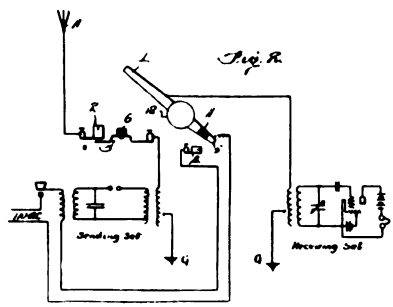
dielectric material formed with bends or folds therein along its length forming pocket-like receptacles for individual armatures of the condenser. The condenser is assembled by inserting the conducting sheets or armatures oppositely in the folds of the continuous strip and terminals taken from the extending edges of the condenser plates.





NUMBER 1,415,179—Radio Controlling Device

1,415,382—J. W. Milnor, filed January 17, 1918, issued May 9, 1922. Assigned to Western Union Telegraph Company.

AMPLIFIER. This invention relates to an amplifier and is described particularly in connection with a cable circuit. The amplifier comprises an electron tube connected to oscillate at low frequency with a tuned vibrating relay operated by the amplifier in synchronism with such oscillations, and arranged to rectify the oscillatory current for operation of a responsive device. Another circuit shows a pair of tubes, one adapted to amplify positive current pulses and the other negative current pulses.

1,415,534—H. P. Donle, filed December 15, 1921, issued May 9, 1922. Assigned to Connecticut Telephone and Electric Company, Incorporated.

VARIABLE RESISTANCE. The patent shows a pair of resistance coils mounted one on the front of an insulated member and

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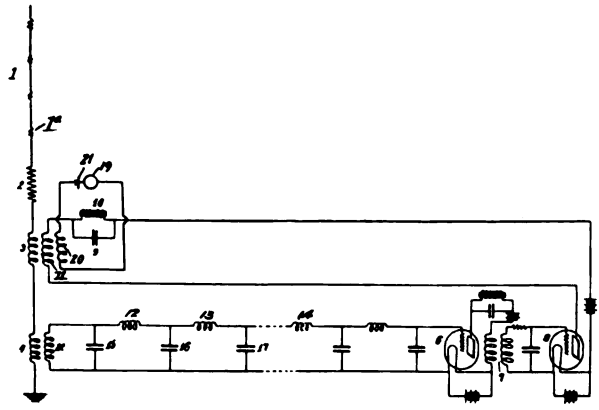
the other on the rear thereof with concentric shafts for moving contact arms independently over the resistance coils. The two shafts are operated from separate knobs which may project thru the face of a panel.

1,415,845—M. I. Pupin and E. H. Armstrong, filed February 10, 1916, issued May 9, 1922.



NUMBER 1,415,845—Selectively Opposing Impedance to Received Electrical Oscillations

SELECTIVELY OPPOSING IMPEDANCE TO RECEIVED ELECTRICAL OSCILLATIONS. The invention relates to a circuit arrangement for a radio receiver in which the time necessary for an electrical action impressed upon the antenna is prolonged before arriving at a local power source or resistance compensator. By the reaction between the incoming signals and the resistance compensator, a negative resistance is produced in the antenna system whereby actions impressed upon the antenna which last a time shorter than the time of their transmission to the local power source will not be aided by the power source. The interaction between the local power source and the antenna system is not instantaneous and therefore the local power source will not be excited to aid an electrical action of a duration shorter than a fixed minimum time interval. When an electrical pulse is impressed upon the antenna it is communicated, as is well known, to the exciting circuit of the resistance compensator 6, 7, 8, thru the mutual inductance 4, 22. This action will be transmitted from 22 to the local energizing circuit over the artificial line, and its time of transmission is determined by the total inductance,

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capacity and resistance of the line. Let L, C, and R be the total inductance, capacity and resistance of the artificial line, then the time of transmission t_1 will be approximately

$$t_1 = 10^{-3}\sqrt{LC} \text{ seconds}$$
$$L = 6 \times 10^{-2} \text{ henrys}$$
$$C = 12 \times 10^{-2} \text{ microfarads}$$
$$t_1 = 8.4 \times 10^{-5} \text{ seconds.}$$

If, then, the time of action of the pulse upon the antenna and the process of discharge of the energy deposited by the pulse upon the antenna is less than 8.4×10^{-5} seconds, the local source of power cannot give any assistance to the pulse or the subsequent process of discharge of the energy deposited by it. Any pulse will set up in the artificial line free oscillations, the duration of which, in the example given, may exceed 8.4×10^{-5} seconds, altho their amplitude will be greatly reduced by the uncompensated high resistance of the antenna. These oscillations can always be adjusted in such a way that their frequencies will be very different from the signaling frequency to which the resistance compensator is selectively adjusted. In the example given above, the highest natural period will be less than 23,000 periods per second if the line consists of six equal sections; and oscillations of this frequency will not be assisted by a resistance compensator selective to a signaling frequency of 25,000 periods per second.

1,415,992—L. M. Clement, filed March 22, 1918, issued May 16, 1922. Assigned to Western Electric Company, Incorporated.

Receiving Station. The patent relates to a receiving apparatus with an arrangement of switches within the circuits of the electron tubes whereby the receiver can be made efficiently responsive to different kinds of signals by quick manipulation of switches. The system is adapted to receive damped waves, or plurally modulated waves or undamped waves with heterodyne reception. Switching arrangements are provided so that single or plural stage amplification may be had.

1,415,999—A. M. Curtis, filed November 1, 1916, issued May 16, 1922. Assigned to Western Electric Company, Incorporated.

Static Reducer for Radio Signals. This invention makes use of the properties of various rectifying crystals which lose much of their rectifying action when the impressed oscillations

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become strong. A carborundum-to-metal contact 8 is employed in the receiving circuit preceded by radio frequency amplifier 5 and followed by audio frequency amplifier 14. The carborundum-to-metal contact 8 in this invention has a characteristic wave similar to Figure 1 showing a symmetrical resistance for large impressed voltage, but asymmetrical for low voltage. If,

Fig. 3.

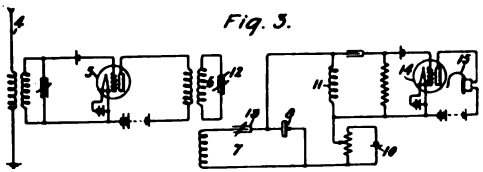
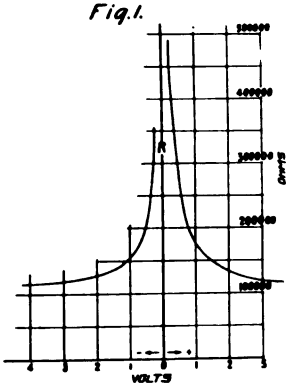


Fig. 1.



NUMBER 1,415,999—Static Reducer for Radio Signals

for example, the instantaneous impressed alternating voltage is three volts, the positive and negative values of the resistance are very nearly the same, namely, 119,000 ohms for the positive value and 120,000 ohms for the negative value. But if the instantaneous voltage is small, say 0.5 of a volt, there is asymmetry of resistance, the positive value being 300,000 ohms and the negative value 200,000 ohms. In the first case there can be no rectification over the portion of the voltage wave which gives equal resistance values for both polarities. What little rectification does occur will be for that fraction of the voltage wave in which the voltage values are all below the minimum value for symmetrical resistance values; if the instantaneous value is large, as illustrated by the first example, that part of the voltage wave which does give rectification will be only a small fraction of the total wave, so that what rectification does occur may be said to be very inefficient. But impressed signals of

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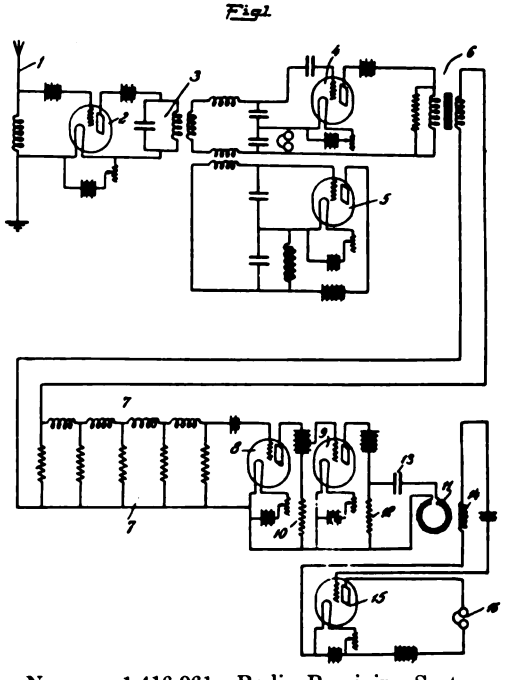
smaller voltage values would be rectified during the complete cycle, as is shown by the latter-mentioned case. Thus, if a small alternating voltage is impressed on a contact of this class, there will, in general, be rectification dependent for its amount on the polarizing voltage; but for alternating voltage high enough to bring the resistance down to the point where it becomes constant and equal for both polarities, the rectification will be relatively much smaller. By a suitable adjustment of a rectifier containing a carborundum-to-metal contact of this type, it is possible to cause relatively strong undesired signals to be very much reduced in most cases, while not affecting materially the strength of the weak signals that are to be read.

1,416,061—M. I. Pupin and E. H. Armstrong, filed December 18, 1917, issued May 16, 1922.



NUMBER 1,416,061—Radio Receiving System Having High Selectivity

RADIO RECEIVING SYSTEM HAVING HIGH SELECTIVITY. Designed for the purpose of separating received signals from natural atmospheric disturbances as well as artificial radio disturbances

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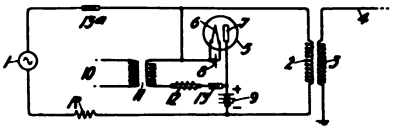
originating at the sending stations of other systems. In the drawing a receiving circuit is shown having a radio frequency amplifier 2 and a regenerative amplifier and detector 4. A local oscillator 5 is employed whereby received oscillations are combined with the local oscillations to produce beats of an audible frequency, usually of about one thousand cycles per second in present practice, but in this invention of a beat frequency of about one hundred cycles per second. These low frequency pulsations are passed thru a wave filter 7 designed to pass such frequencies and, preferably, all lower frequencies, but to attenuate and suppress frequencies of substantially higher range, as frequencies of two hundred or over. These low frequency pulsations are passed thru amplifiers 8 and 9 and energize the rotor 11 of an induction motor. The stator of the induction motor is shown at 14 connected to the input circuit of audio frequency amplifier 15, giving as a result pulsations of 1,100 cycles and 900 cycles frequency in the telephones 16.

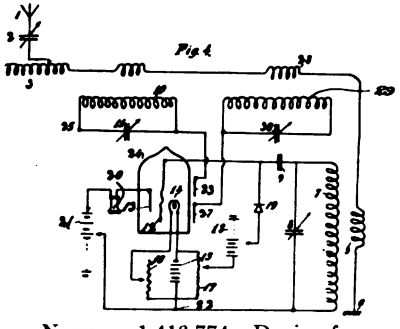
1,416,077—De Witt C. Tanner. Filed March 8, 1919, issued May 16, 1922. Assigned to Western Electric Company.



NUMBER 1,416,077—System for Electrical Signaling

SYSTEM FOR ELECTRICAL SIGNALING, in which modulation of high frequency oscillations is secured by use of a two-electrode fube.

1,416,774—C. Bardeloni, filed April 17, 1920, issued May 23, 1922.



NUMBER 1,416,774—Device for Receiving Radio Signals

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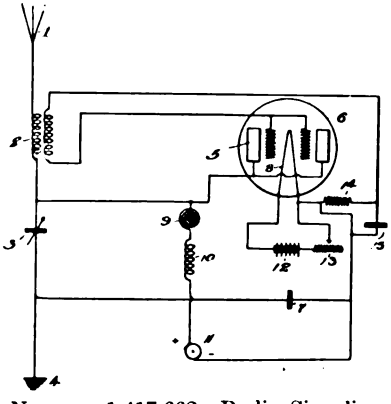
Device for Receiving Radio Signals. The patent shows a circuit arrangement designed for reduction of interference and strays in radio reception.

1,417,662—L. De Forest, filed June 16, 1917, issued May 30, 1922.



Number 1,417,662—Radio Signaling System

Radio Signaling System. A circuit is shown in this patent for connection of an electron tube with an antenna ground system. In the drawing 1 designates the antenna which is connected thru inductance 2 and variable condenser 3 to the ground 4. The plate electrode 5 of the oscillion 6 is connected to one terminal of the condenser 3 and the other terminal of the condenser 3 is connected thru a condenser 7 to the filament electrode 8 of the tube. The plate electrode 5 is also connected thru impedance coil 9, inductance 10 to the source of plate potential 11 back to the filament. A tickler circuit is formed with the grid and filament thru condenser 15 shunted by high resistance 14. The tickler circuit is inductively associated with the inductance 2 of the antenna system. The circuit is particularly designed for electron tube transmitting circuits.

1,417,912.—P. C. Hewitt, filed June 24, 1916, issued May 30, 1922.

Vacuum Electric Apparatus, comprising a tube having two surfaces substantially parallel and facing each other with a narrow space between them in which are mounted one electrode in the form of a filament and at least one electrode serving as an

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anode. Means exterior of the flat surfaces are provided for controlling the reactions within the tube such as an adjacent transmitter mouthpiece by which sound vibrations are directed against the flat walls of the tube or a magnetic field adjacent the flat walls of the tube.

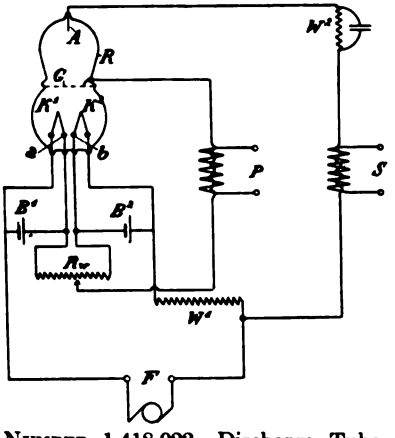
1,417,913—A. Heyland, filed July 28, 1914, issued May 30, 1922.

Apparatus for Generating High Frequency Electric Currents of the rotor and stator alternator type. The patent relates to a pole and armature system for a machine of this character wherein the magnetic pieces are surrounded by connected electrically conducting metal adapted to bridge the pole tips of opposite polarity.

According to this invention the active rotor iron is disposed solely at the surface of the rotor and always in that segment which bridges the slot separating the pole tips of two stator poles, the segments underneath the stator poles being inactive. The stator field is closed tangentially over the corresponding rotor segments.

1,418,022—E. Reisz, filed June 5, 1915, issued May 30, 1922.

Fig. 1



Number 1,418,022—Discharge Tube Relay for Undulatory Currents

Discharge Tube Relay for Undulatory Currents, in which the cathode is divided into two parts, the circuits being separated by a resistance R_w and the plate circuit including

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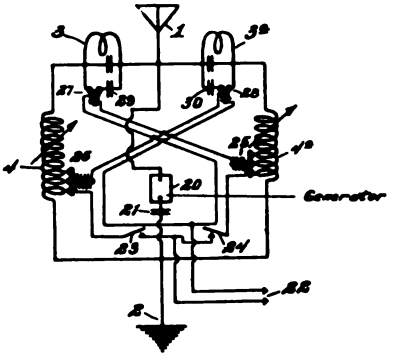
resistances W^1 and W^2. A difference of potential between the two parts of the cathode is secured by which strong ionization is produced.

1,418,066—T. R. Bunting, filed June 2, 1920, issued May 30, 1922.



NUMBER 1,418,066—Radio Transmitting System

RADIO TRANSMITTING SYATEM, for duplex operation permitting two messages to be transmitted simultaneously and independently by one antenna. The system includes two parallel radiating circuits consisting of the same antenna and ground, between which are two electrical circuits each of which includes a tuning inductance and an impedance circuit composed of an inductance shunted by a capacity, each impedance circuit to be tuned to the frequency of the opposite radiating circuit, and the two radiating circuits to be tuned to oscillate at frequencies sufficiently different to render negligible the impedance of each impedance circuit to the oscillating current of the radiating circuit of which it is a part.

1,418,285—J. R. Carson, filed October 10, 1918, issued June 6, 1922. Assigned to American Telephone and Telegraph Company.

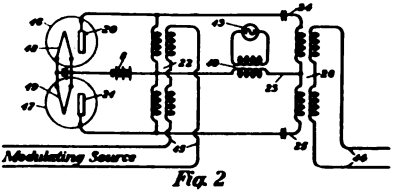


Fig. 2

NUMBER 1,418,285—Translating Circuits

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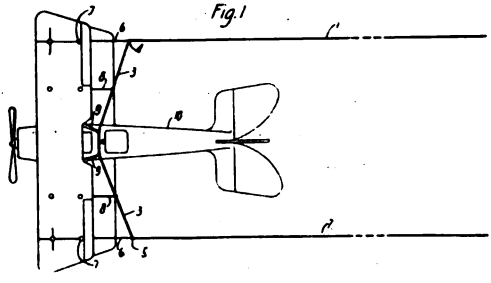
TRANSLATING CIRCUITS, for modulating high frequency oscillations in which two electrode vacuum tubes or equivalent devices having unilateral conductivity are employed.

1,418,518—E. F. Bell, filed September 20, 1920, issued June 6, 1922.

QUENCHING ROTARY SPARK CAP, comprising an enclosed casing, a set of separated stationary electrodes mounted in the casing, and a rotor carrying moving electrodes which may be brought adjacent the stationary electrodes forming sparking surfaces. A spring is provided to prevent the rotor from moving longitudinally upon its bearing.

1,418,729—A. A. Oswald, filed April 25, 1919, issued June 6, 1922. Assigned to Western Electric Company, Incorporated.



NUMBER 1,418,729—Portable Radiating System

PORTABLE RADIATING SYSTEM for Aircraft or Moving Vehicles. The invention employs a plurality of trailing wires supported from the outer portions of the wings of an airplane. The wires are connected in parallel and form the antenna system against the metallic structures on the airplane which form the counterpoise. The use of a pair of trailing wires in lieu of a single trailing wire reduces the directional property of the antenna and permits shorter trailing length of the antenna, reducing the possibility of entanglements and breaking away of the antenna.

1,418,739—E. O. Scriven, filed June 4, 1917, issued June 6, 1922. Assigned to Western Electric Company, Incorporated.

OSCILLATION GENERATOR, having in the input circuit of the tube a path of high impedance for the direct current from the source of voltage of the output circuit and a path of low imped-

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ance for the resultant oscillations. The object of the circuit arrangement is to provide means for generating oscillations, the intensity of which is independent of small changes in the impedance between the output electrodes of the evacuated vessel, so that approximately similar tubes may be used in the oscillation generator without producing any change in the high frequency output.

1,418,788—J. H. Hammond, Jr., filed July 14, 1913, renewed October 9, 1915, issued June 6, 1922.

System for Control of Bodies by Radiant Energy.

1,418,789—J. H. Hammond, Jr., filed July 14, 1913, renewed May 2, 1922, issued June 6, 1922.

System for Control of Bodies by Radiant Energy.

1,418,790—John H. Hammond, Jr., filed August 14, 1913, renewed July 11, 1917, issued June 6, 1922.

Radio Dynamic Control of Gyroscopes.

1,418,791—John H. Hammond, Jr., filed June 22, 1914, renewed May 3, 1922, issued June 6, 1922.

System for Control of Moving Bodies by Radiant Energy.

1,418,792—John H. Hammond, Jr., filed August 6, 1914, renewed May 3, 1922, issued June 6, 1922.

System for Control of Moving Bodies by Radiant Energy.

1,418,793—John H. Hammond, Jr., filed December 20, 1915, renewed March March 12, 1919, issued June 6, 1922.

System of Teledynamic Control for Dirigible Bodies.

1,418,794—John H. Hammond, Jr., filed April 8, 1913, renewed September 22, 1916, issued June 6, 1922.

System of Teledynamic Control.

1,418,795—John H. Hammond, Jr., filed January 12, 1916, renewed March 14, 1918, issued June 6, 1922.

Launching Mechanism for Torpedoes.

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1,418,796—John H. Hammond, Jr., filed July 15, 1913, renewed December 13, 1918, issued June 6, 1922.

TELEDYNAMIC CONTROL.

1,418,797—John H. Hammond, Jr., filed March 29, 1913, renewed January 30, 1919, issued June 6, 1922.

SYSTEM OF SUBMARINE-MINE LAYING.

1,418,869—John H. Hammond, Jr., filed November 20, 1913, renewed February 9, 1918, issued June 6, 1922.

TELEDYNAMIC CONTROL.

1,418,870—John H. Hammond, Jr., filed August 14, 1913, renewed January 30, 1919, issued June 6, 1922.

RADIODYNAMIC TORCH LAUNCHING MECHANISM.

1,419,376—J. H. Hammond, Jr., filed November 27, 1909, renewed November 6, 1915, issued June 13, 1922.

RADIO CONTROL APPARATUS. The patent shows a mechanism arranged for control of a vehicle or vessel such as a torpedo boat or dirigible torpedo from a distance.

1,419,377—J. H. Hammond, Jr., filed August 1, 1913, renewed March 19, 1919, issued June 13, 1922.

RADIODYNAMIC OCCULTING SYSTEM for cutting off and concealing the emissions of a searchlight by radio control from a distance. The patent shows a searchlight having a swinging shutter and a compressed air mechanism for operating said shutter. A rotary valve is provided operated by reciprocatory magnetic means controlled by the radio receiver from the distant control station which permits the access of the compressed air to operate the mechanism controlling the swinging shutter.

1,419,460—F. Lowenstein, filed November 29, 1918, issued June 13, 1922.

COMBINED KEY AND SWITCH, for a radio transmitting system. The key for closing the transmitting circuits is carried by a lever arm which is pivotally mounted to swing over wave changer contacts. The unit combines the key and a wave changer switch, the key knob serving both for code manipulation and as a handle for operating the switching lever.

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1,419,528—H. W. Weinhart, filed October 25, 1918, issued June 13, 1922. Assigned to Western Electric Company, Incorporated.

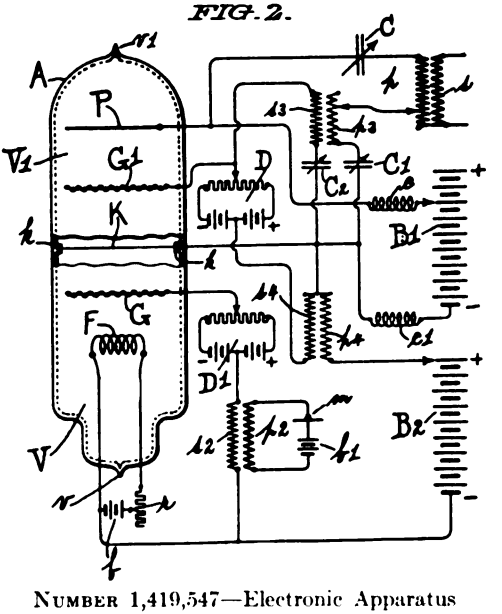
ELECTRON DISCHARGE DEVICE, in which provision has been made for the expansion of the electrodes under the influence of heat and electron bombardment to which the tube is subjected. Loose guiding connections are provided for the electrodes slidably mounted on rigid electrode supports whereby distortion of the electrodes under increase in temperature is eliminated.

1,419,530—W. Wilson, filed August 12, 1918, issued June 13, 1922. Assigned to Western Electric Company, Incorporated.

THERMIONICALLY ACTIVE SUBSTANCE for use in electron tubes. The invention describes a treatment of ductile metals of the iron group, such as iron, nickel or cobalt, whereby their thermionic activity is increased and made comparable to that of oxide coated platinum filaments. The filament of the invention comprises a core of a ductile metal of the iron group subjected to a coating of strontium and barium oxides.

1,419,547—C. D. Ehret, filed November 12, 1918, issued June 13, 1922.

FIG. 2.



NUMBER 1,419,547—Electronic Apparatus

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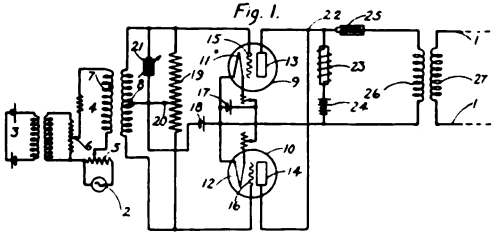
ELECTRONIC APPARATUS, comprising a tube A divided by cathode K into two chambers V and V_1, both of which and particularly V are preferably closed to the outer atmosphere. The cathode K is in the form of a thin plate sealed thruout its periphery at k, whereby it completely seals chambers V and V_1 from each other and forms a wall common to them.

The body F emits electrons which bombard or impinge upon the cathode K which in consequence becomes an electron-emitting body. The number of electrons so re-emitted may greatly exceed the number of electrons emitted by body F, and so permit or cause a large current between anode P and cathode K. That current may be caused to vary in amplitude or fluctuate by varying the potential of electrode or grid G_1, which may be connected to cathode K thru transformer secondary s^1 and the potentiometer D which serves in known manner normally to hold grid G^1 at any suitable potential. When a telephonic, oscillating or other varying or fluctuating current is passed thru transformer primary p^1, the potential of grid G^1 and therefore, the large current in the circuit of anode P, is correspondingly varied. And that current in transformer primary p may induce an alternating or fluctuating current similarly varying in the secondary s.

1,419,562—R. V. L. Hartley, filed September 29, 1919, issued June 13, 1922. Assigned to Western Electric Company, Incorporated.



NUMBER 1,419,562—Modulator or Detector

MODULATOR OR DETECTOR, having a balanced circuit made up of a pair of three electrode tubes. The cathodes of the separate tubes are connected directly together. A circuit is provided for causing equal and opposite instantaneous variations of the potentials of the grids of the separate tubes to effect modulation of a sustained source.

1,419,797—E. F. W. Alexanderson, filed February 13, 1919,

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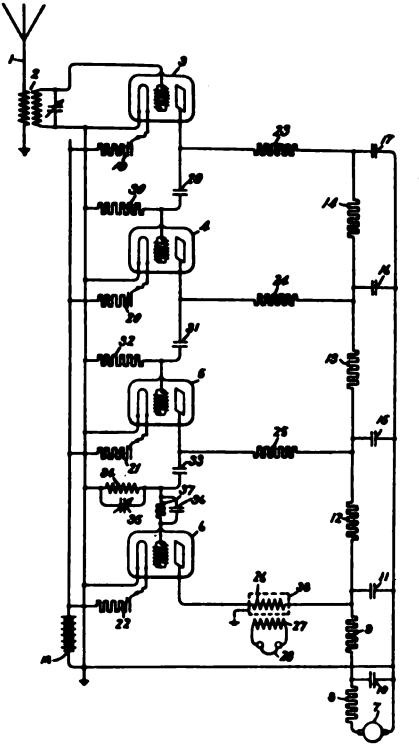
issued June 13, 1922. Assigned to General Electric Company.



NUMBER 1,419,797—Amplifying System

AMPLIFYING SYSTEM, provided with filter connections between the successive amplifiers of the system. The object of the invention is to provide means for supplying the operating current to the plate circuits of the amplifiers in such a way that a source of current of somewhat variable potential may be employed without injuriously affecting the operation of the amplifiers. Another object of the invention is to provide a connection which will prevent the transmission from one amplifier to another of potential variations of undesired frequency, which may be set up in any of the circuits. Still another object of the invention is to provide connections which will eliminate the tendency of the amplifiers to act in such a way as to generate oscillations.

1,420,055—H. W. Nichols, filed December 18, 1920, issued June

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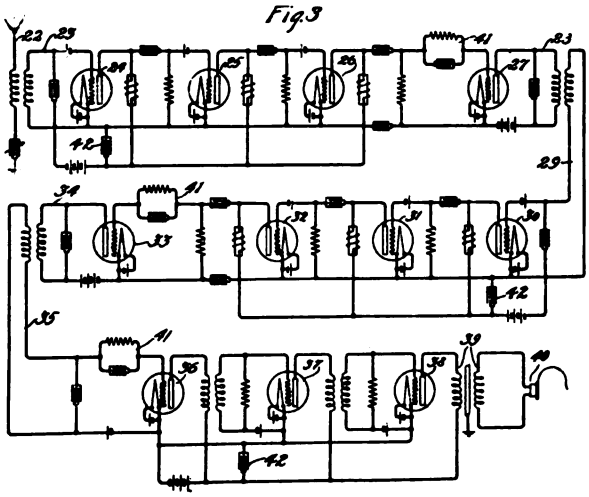
20, 1922. Assigned to Western Electric Company, Incorporated.



NUMBER 1,420,055—Selective Receiving System

SELECTIVE RECEIVING SYSTEM, which involves detecting incoming modulated signal waves, selecting a harmonic frequency of said waves, detecting the said waves of the selected frequency and then observing the signal. In Figure 3 of the patent the receiving circuit is shown comprising antenna system 22 associated with a resonant circuit 23 tuned to the frequency of the incoming signal modulated waves. The high frequency current is amplified by a three-stage amplifying system including the amplifiers 24, 25, and 26 and detected by the detector 27, which includes in its output circuit the circuit 28 tuned to the first even harmonic frequency of the incoming waves. The latter circuit is inductively associated with the circuit 29 selective of the same frequency, whereby the selected oscillations are transmitted thereto and impressed across the input circuit of the amplifier 30. The variable current in the output circuit of the tube 30 is amplified by devices 31 and 32 and impressed across the input circuit of the detector 33, the output circuit of which includes the circuit 34 tuned to the first even harmonic of the current traversing its input circuit, that is, the second even harmonic of the carrier frequency.

The current selected by the circuit 34 is transferred to the resonant circuit 35 tuned to the same frequency which is con-

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nected across the input circuit of the detector 36. After amplification by the amplifiers 37 and 38 this current is transmitted through the transformer or repeating coil 39 to the receiver 40.

1,420,257—J. H. Hammond, Jr., filed January 21, 1910, renewed December 7, 1918, issued June 20, 1922.

System and Apparatus for Automatic Wave Selection, wherein signals are transmitted in a predetermined order on different wave lengths and received on a receiver which is rendered responsive to the signals on the succeeding sections of wave length in the same order in which they are transmitted.

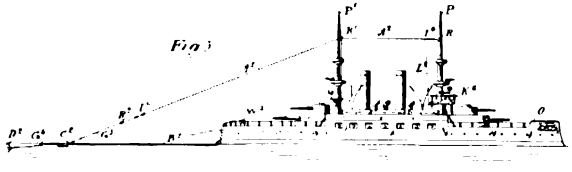
1,420,189—A. R. Goodwin, filed September 8, 1921, issued June 20, 1922. Assigned to Chelsea Radio Company.

Variable Grid Resistance. The leak resistance is provided at different steps with switch points and a blade which moves over said points and selects pre-determined value of leak resistance. In this way the grid leak may be made variable from, for example, one-half million ohms to five million ohms in steps of approximately one-half million ohms.

1,420,254—J. H. Hammond, Jr., filed May 20, 1912, renewed December 12, 1917, issued June 20, 1922.

Electric Wave Transmission system employing a fluid stream as a radiating antenna which stream is automatically and irregularly varied, changing its capacity accordingly. Continuous oscillations are superposed on the antenna system, and groups of waves of constantly and irregularly varying amplitude radiated.

1,420,255—J. H. Hammond, Jr., filed February 27, 1913, renewed October 23, 1918, issued June 20, 1922.



No. 1,420,255—Antenna for Radio Transmission Systems

Antenna for Radio Transmission Systems, comprising a towing anchor which may be attached to the antenna conductors and extended out from a vessel. The antenna may be extended

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to much greater length than is possible to obtain upon the vessel proper, and in this way secure an increase in antenna capacity.

1,420,256—J. H. Hammond, Jr., filed February 25, 1913, renewed October 24, 1918, issued June 20, 1922.

SYSTEM OF TELEDYNAMIC CONTROL, wherein a radio transmitter is arranged to emit a continuous train of waves increased and decreased in amplitude at a pre-determined periodicity. Means are provided selectively to vary this periodicity. At the receiver, means selectively responsive to the variation in periodicity are provided connected to the mechanism to be distantly controlled.

1,420,258—J. H. Hammond, Jr., filed September 3, 1913, renewed April 14, 1919, issued June 20, 1922.

SYSTEM FOR THE RADIO CONTROL OF MOVING BODIES, such as a torpedo ship, land vehicle or an aeroplane. The patent shows mechanism employed at the transmitter and at the receiver for securing the distant control.

1,420,295.—R. W. Tait, filed October 12, 1921, issued June 20, 1922.

COMBINED KNOB AND DIAL FOR RADIO APPARATUS. This patent shows an insulated knob and a dial arranged upon an instrument shaft or spindle. A plurality of resilient jaws are provided which engage and grip the shaft when the knob and dial are screwed together as a unit.

1,420,485—G. F. Johnson, filed May 18, 1920, issued June 20, 1922.

VARIABLE ELECTROSTATIC CONDENSER, having a spring acting against a shoulder formed on the shaft carrying the rotary plates and pressing the rotary plates into accurate center spacing with relation to the stationary plates of the condenser.

The following partially complete list of registered trade-marks will be of interest to the members of THE INSTITUTE OF RADIO ENGINEERS, as showing the character of marks being registered in the Patent Office covering the sale of radio apparatus:

Registration Number 113,751—"Lenzite" for detector crystals.
Registration Number 129,698—"Radio Amateur News" for periodicals.
Registration Number 140,120—"Radio News" for periodicals.

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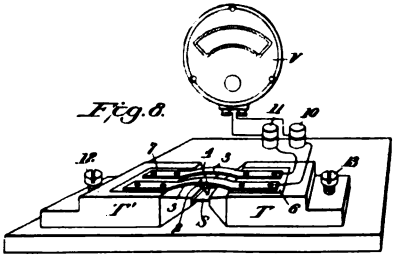
Registration Number 133,313—"Radiophone" for radio apparatus.
Registration Number 133,314—"Radiofone" for radio apparatus.
Registration Number 150,948—"Radiotron" for electron tubes.
Registration Number 152,961—"Radiola" for radio apparatus.
Registration Number 153,172—"Radio Mfg. Co." (Mark arranged within a triangular ornamentation) for radio appaatus.
Registration Number 153,238—Representation of Magnavox loud speaker with lion head protruding from horn, for loud speaking telephones.
Registration Number 157,518—"Vocaloud" for loud speakers.
Registration Number 159,777—"Air O Phone" for radio apparatus.

NOTE—The following patents should be considered as included with the preceding digests.

1,407,147—Wm. N. Goodwin, Jr., filed July 27, 1916, issued February 21, 1922. Assigned to Weston Electrical Instrument Company.



NUMBER 1,407,147—Thermal Ammeter

THERMAL AMMETER, for measurement of alternating currents designed especially for measurement of high frequency currents. An indicating instrument is employed to measure the current passing thru a conductor or "hot wire" connected to its terminals by the difference in the temperatures (produced by the passage of the current) between the mid-portion, preferably the center and ends of the conductor, the conditions being so controlled that this temperature difference will be dependent principally upon the thermal and electrical conductivities of the material of which the heating conductor is made, and only to a slight extent upon external or other influences.

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The development of the present form of thermal-ammeter is based upon the principle, as demonstrated by mathematical analysis, that if a conducting strip or wire of uniform cross sectional area, carrying a current, is cooled only by conduction thru the body of the strip itself and not directly cooled by the surrounding air, the difference in temperature between any two points along the strip, in general, or, in particular, between the center of the strip and the terminals to which the strip is joined, is dependent upon the difference of electrical potential between these points and upon the thermal and electrical conductivities of the material of which the conducting strip is made. The relation between these four quantities as found is exhibited in the following equation.

$$T = \frac{V^2}{8K\rho}$$

where
T = temperature difference between center of strip and terminal,
V = difference of potential between the terminals,
K = thermal conductivity of strip material, and
ρ = specific resistance of the strip material.

1,410,890—J. R. Carson, filed August 8, 1918, issued March 28, 1922. Assigned to American Telephone and Telegraph Company

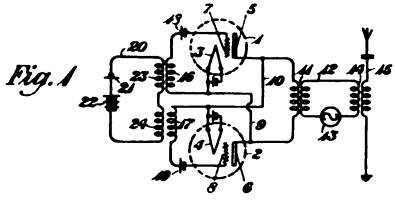

Fig. 1

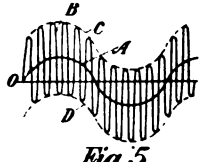

Fig. 5

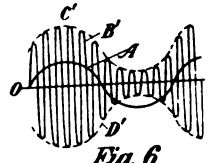

Fig. 6

NUMBER 1,410,890—Method of and Means for Modulating Carrier Oscillations

METHOD OF AND MEANS FOR MODULATING CARRIER OSCILLATIONS, wherein both halves of the carrier wave is modulated

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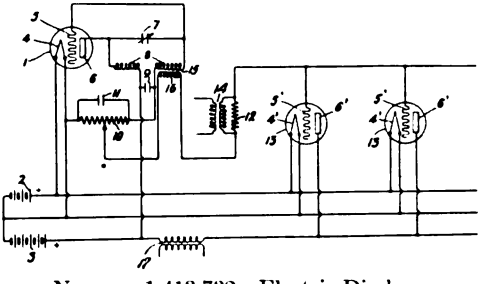
in accordance with the signal. Oscillations from the source 13 are simultaneously impressed upon the antenna 15 and the output circuits of the tubes 1 and 2, the half-wave of one polarity flowing from filament 3 to plate 5 of tube 1, and the half-wave of the opposite polarity flowing from filament 4 to plate 6 of tube 2. The amount of energy diverted from the antenna 15 to the tubes 1 and 2 will depend upon the conductivity of the tubes which is determined by the potential on the grids 7 and 8. Since the potential of these grids with respect to the corresponding filaments is the same and varies in accordance with the variation in current flow in the circuit 20 produced by the transmitter 21, the amount of energy diverted thru the tubes will vary in accordance with the signals produced by the transmitter and the amount of energy radiated by the antenna will be modulated in accordance with the signals. Furthermore, since the conductivity of the two tubes at any given instant is the same, both the positive and the negative halves of the transmitted oscillations will be modulated alike. Altho the tubes are unilaterally conductive, and hence only half waves flow thru each tube, their conductivities or impedances are equal with respect to positive plate-filament potentials, since the grid-filament potentials are equal.

1,413,732—R. A. Heising, filed October 2, 1916, issued April 25, 1922.



NUMBER 1,413,732—Electric Discharge Apparatus

ELECTRIC DISCHARGE APPARATUS, in which the necessity for polarizing grid batteries is eliminated and negative potential supplied thru the action of an oscillator. The system is particularly adapted for aircraft sets in simplifying the apparatus and reducing its weight.

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PROCEEDINGS OF
The Institute of Radio Engineers

Volume 10 OCTOBER, 1922 Number 5

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CORRECTION

On page 131 of the PROCEEDINGS, April, 1922 (Volume 10, Number 2), for the final equation:

$$R_r = 32.9 \frac{(1-\gamma^2)}{\left(\frac{\lambda}{\lambda_o}\right)} [1+\gamma+\gamma^2]$$

read the following equation:

$$R_r = 32.9 \frac{(1-\gamma)^2}{\left(\frac{\lambda}{\lambda_o}\right)^2} [1+\gamma+\gamma^2]$$

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RECEIVING MEASUREMENTS AND ATMOSPHERIC DISTURBANCES AT THE UNITED STATES NAVAL RADIO RESEARCH LABORATORY, BUREAU OF STANDARDS, WASHINGTON, MAY AND JUNE, 1922*

By

L. W. Austin

(United States Naval Radio Laboratory, Washington, D. C.)

(*Communication from the International Union for Scientific Radio Telegraphy*)

The measurements for May and June have been taken in the manner already described. The tables show the increase in strength of the atmospheric disturbances with the advancing season. The signal observations in May are, in general, similar to those of the earlier months except for a decrease in the afternoon values. This decrease in afternoon strength becomes very marked in the June table, which also shows the great differences in absorption at different wave lengths. During the greater part of the month, Nauen, with a wave length of 12,500 meters, became unmeasurable at three o'clock thru the disturbances and interference, falling probably to less than 3 micro-volts per meter, while Lafayette, at a wave length of about 24,000 meters, except for three or four days, did not fall much below one-fourth of its morning value.

This afternoon absorption appears to vary with the location of the receiving station, since, according to my observations made in 1919, it was very slight at Bar Harbor, Maine, but appeared to be fairly uniform for all the coast region lying between New York and Washington, as far as our observations went. The nature of this absorption is not yet understood. It appears to be more common in the warmer regions and on damp warm afternoons. Since it is almost as important as the atmospheric disturbances in interfering with reception during several hours a day in the warm months, it is well worthy of careful investigation.

*Received by the Editor, July 19, 1922.

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FIELD INTENSITY OF NAUEN AND STATIC ($\lambda = 12{,}500$ m.) IN MAY, 1922, IN MICRO-VOLTS PER METER

Date	A. M.		P. M.	
	Signal	Static	Signal	Static
1	38.5	100	....	....
2	43.0	80	....	....
3	47.0	20	21.5	100
4	30.0	60	....	150
5	26.0	100	....	....
6	....	....	11.0	100
8	34.0	80	....	150
9	47.0	60	....	....
10	56.0	80	....	....
11	34.0	50	....	....
12	38.5	150	....	....
13	30.0	100	....	....
15	34.0	60	....	....
16	30.0	500	....	....
17	38.5	240	....	....
18	....	....	34.0	100
19	21.5	306	....	....
20	....	....	....	....
23	43.0	50	....	....
25	64.0	40	....	....
26	43.0	50	....	....
27	50.0	60	....	....
29	43.0	50	....	....
31	38.5	50	....	....
Average	39.8	108.8	22.2	120

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FIELD INTENSITY OF LAFAYETTE AND STATIC ($\lambda = 23{,}400$ m.) IN MAY, 1922, IN MICRO-VOLTS PER METER

Date	A. M.		P. M.	
	Signal	Static	Signal	Static
1	140.0	300	85.0	400
2	110.0	150	70.0	1,000
3	110.0	60	60.0	1,000
4	80.0	200	20.0	800
5	75.0	900	....	1,000
6	25.5	400	18.0	1,200
8	....	....	17.0	260
9	110.0	200	45.0	300
10	120.0	200	15.5	5,800
11	115.0	300	3.5	1,000
12	....	....	....	1,680
13	75.0	600	....	....
15	....	500	30.0	200
16	45.0	1,500	....	....
17	31.0	982	....	....
18	....	....	15.5	200
19	45.0	840	30.0	1,500
20	15.5	1,500	....	1,000
23	75.0	60	12.5	1,265
25	200.0	80	....	....
26	100.0	100	50.0	300
27	80.0	200	25.0	80
29	115.0	150	17.0	500
31	75.0	80	15.5	200
Average	87.1	438.0	31.1	990

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FIELD INTENSITY OF LAFAYETTE AND STATIC ($\lambda = 23{,}400$ m.) IN JUNE, 1922, IN MICRO-VOLTS PER METER

Date	A. M.		P. M.	
	Signal	Static	Signal	Static
1	50.0	200	20.0	2,000
2	65.0	80	30.0	200
3	25.0	50	35.0	250
4	65.0	60	30.0	1,000
8	75.0	80	20.0	100
9	25.0	60	35.0	1,500
12	45.0	60	25.0	600
13	45.0	300	20.0	1,000
14	50.0	100	30.0	300
15	100.0	100	20.0	650
16	65.0	300	15.0	890
17	60.0	400	....	....
19	50.0	200	....	1,650
20	30.0	400	20.0	970
21	....	....	30.0	300
22	65.0	600	20.0	560
23	40.0	200	....	690
24	95.0	300	....	....
26	....	....	15.0	560
27	60.0	400	....	680
28	75.0	100	....	690
29	75.0	560	....	560
30	65.0	200	....	680
Average	58.3	201.8	24.3	753.8

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FIELD INTENSITY OF NAUEN AND STATIC ($\lambda = 12{,}500$ m.) IN JUNE, 1922, IN MICRO-VOLTS PER METER

Date	A. M.		P. M.	
	Signal	Static	Signal	Static
2	38.0	40	11.5	100
3	38.0	60	....	.....
4	30.0	40	....	....
6	....	....	11.0	400
7	60.0	30	....	....
8	34.0	50	....	300
9	30.0	17	....	800
10	....	80	....	....
12	26.0	50	....	400
13	21.5	100	....	600
14	26.0	40	....	80
15	26.0	50	....	200
16	21.5	150	....	400
17	26.0	60	....	600
19	21.5	80	....	....
20	13.0	100	....	680
21	43.0	200	11.5	640
22	34.0	300	....	420
23	36.0	30	....	500
24	47.0	40	17.0	640
26	55.0	200	21.5	300
27	26.0	150	....	800
28	19.0	80	....	....
29	60.0	80	21.5	500
30	38.0	60	....	....
Average	33.5	86.9	15.7	464.4

SUMMARY: The daily values of the morning and afternoon strength of signals during May and June, 1922, from Nauen (12,500 meters) and Lafayette (24,000 meters), together with the strength of atmospheric disturbances are given in tabular form.

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THE DYNATRON DETECTOR*

A NEW HETERODYNE RECEIVER FOR CONTINUOUS AND MODULATED WAVES

By

Albert W. Hull, E. F. Hennelly, and F. R. Elder

(General Electric Company, Schenectady, New York)

Introduction

The characteristic features of the dynatron have been fully described in a previous paper.[1] It was briefly pointed out that an oscillating pliodynatron may be used for heterodyne reception of continuous waves. This application has now been thoroly investigated, and shows unique features, which it is the purpose of this paper to describe.

The practical merits of the dynatron detector may be briefly summarized as follows: In comparison with pliotron self-heterodyne, which may be taken as the best of the systems hitherto used, the dynatron has three marked advantages:

(1) The local oscillations are not fed back into the antenna.

(2) Stray disturbances of other than signal frequency are not rectified, and hence do not produce audible disturbance.

(3) The filament may be heated by alternating current without audible disturbance.

In sensitiveness and selectivity, there is little to choose between the dynatron and self-heterodyne. In ease and stability of operation, the dynatron has considerable advantage over the self-heterodyne, and is to be compared with the separate heterodyne using two pliotrons.

Description of Dynatron

The distinguishing feature of the dynatron is its utilization of secondary or *impact* electron emission. When an electron strikes a metal plate, it generally enters it, and either attaches

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[1]Hull, Proceedings of The Institute of Radio Engineers, 6, pages 5-35, February, 1918.

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itself to one of the atoms of the plate or takes part in the electric current thru the plate and connecting wires. If the electron strikes the plate with sufficient velocity, however, its impact delivers so much energy to the electrons in the surface of the plate that some of them are able to escape. The number thus liberated increases with the velocity of impact, and may exceed the number striking, causing the current to the plate to reverse in sign. For example, if each electron that strikes the plate splashes out two, and these two escape to some other electrode, it is evident that the plate will not be gaining electrons but losing them. The electrons that are splashed off are sometimes called secondary electrons, but the name *impact electrons* is more appropriate and will be used hereafter. The plate that emits impact electrons will be called the *impact electrode*, or, when it is part of a dynatron, the *dynode*.

When the impact electrode is at a higher potential than its surroundings, so that there is no place for the impact electrons to go, they will return to the impact electrode. There is then nothing to indicate that they ever left this electrode. This is why impact emission from the plate of a pliotron amplifier is never observed. In order to utilize the impact emission there must be present another electrode at higher potential than the impact electrode, so placed that its electric field will carry off the impact electrons as fast as they are emitted. The problem of dynatron construction is to place this high potential *anode*, as it will be called, as near as possible to the impact electrode or dynode, without intercepting or deflecting the electrons so that they fail to strike the dynode. This conditioni s satisfied by a slight modification of standard pliotron construction.

The dynatron consists of a filament, grid, and surrounding cylinder, like the pliotron, but the grid is placed as close as possible to the surrounding cylinder and used as anode, the cylinder being used as dynode. (Figure 1.) The electrons from the filament fly freely thru the grid anode to the surrounding dynode cylinder, and the impact electrons they produce are attracted and carried away by the grid. It is obvious that the functions of grid and cylinder may be interchanged, that is, the grid may be used as dynode and the cylinder as anode. This is very desirable for many purposes, especially where the grid is so constructed as to intercept nearly all the primary electrons. In the tests described in this paper, however, the grid is used as anode.

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The volt-ampere characteristic of the dynatron is shown in Figure 4. The negative slope of the portion AB represents the loss of impact electrons, the number of which increases with velocity of impact of the primaries, that is, with increasing dynode voltage. This *negative resistance* represents available power (at the expense, of course, of power supplied to the anode) which may be used to neutralize losses in the circuit or to produce oscillations, as described later.

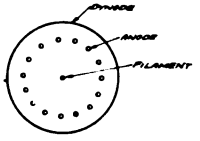

FIGURE 1 (a)—Cross-section sketch of dynatron

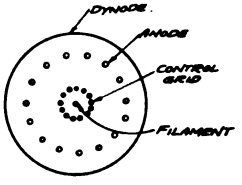

FIGURE 2 (a)—Cross-section of pliodynatron

The magnitude of the ordinates in Figure 4 depends on the magnitude of the current of primary electrons passing from the filament thru the anode to the dynode. This primary current may be controlled by a grid, close to the filament, exactly as in the pliotron. A dynatron containing such a *control grid*, in addition to the anode grid, is called a *pliodynatron* (Figure 2). Figure 5 shows the volt-ampere characteristic of the pliodynatron which was used for the oscillograms in Figures 11 and 12, at three different voltages of the control grid. The three curves are exactly similar, the scale of ordinates only being changed. It will be noted that the change of grid voltage from zero to $+10$ produces much greater amplification than the change from -10 to zero, in accordance with the well-known parabolic law of pliotron amplification.

Instead of using a control grid for controlling the primary emission, one may use a magnetic field, as in the magnetron. In this case the anode is preferably made of radial slats, and both anode and dynode are in the form of circular cylinders concentric with the filament, as shown in Figure 3. The control current passes thru a solenoidal coil wound on the tube, producing a magnetic field parallel to the filament. This magnetic field deflects the electrons so that fewer of them are able to get thru between the slats to the dynode. If the slats are set at a slight angle with the radius, as in Figure 3, a magnetic field in one direction will cause

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an increase, in the other direction a decrease, in the number of electrons that get thru, giving a nearly linear amplification. Figure 6 shows the volt-ampere characteristics, for three different

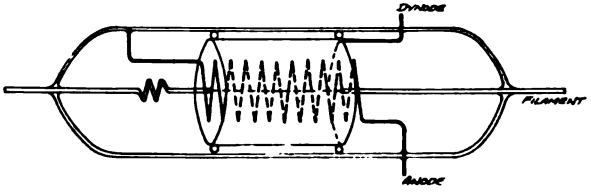

FIGURE 1 (b)—The arrangement of electrodes in the dynatron

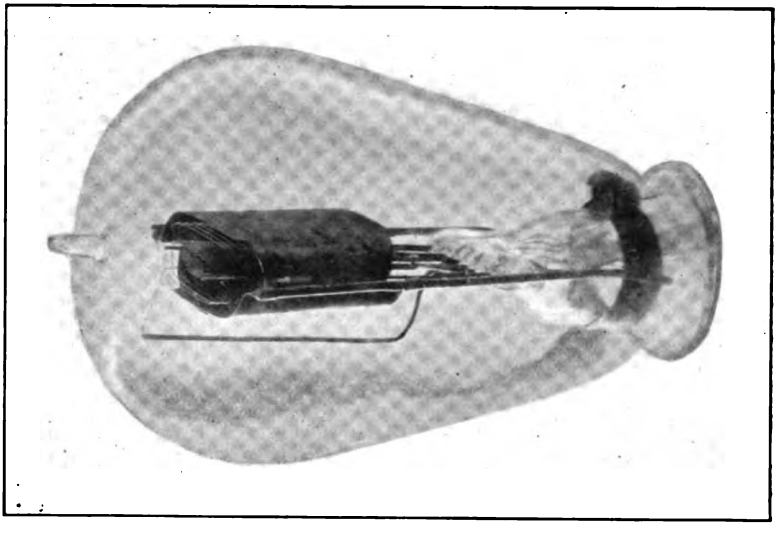

FIGURE 2 (b)—Laboratory model of pliodynatron

values of magnetic field, of the magnetron used in taking the oscillograms of Figures 13-17.

OPERATION

The pliodynatron detector circuit is shown in Figure 7. The signal is impressed on the grid in the usual way. The anode is connected directly to the source of high potential E, preferably about 110 volts, altho any potential above 40 volts is satisfactory if the tube is designed for it. The dynode is connected thru a tuned circuit L, C, and telephones T to a lower potential E_o, preferably the potential at which the dynode current is zero

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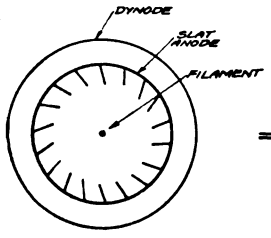

FIGURE 3 (a)—Cross-section of magnetically controlled dynatron

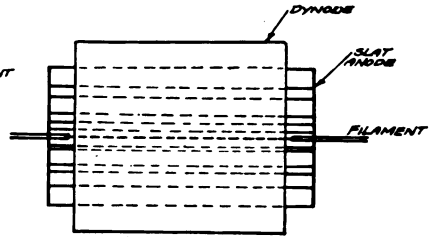

FIGURE 3 (b)—Longitudinal section of magnetically controlled dynatron

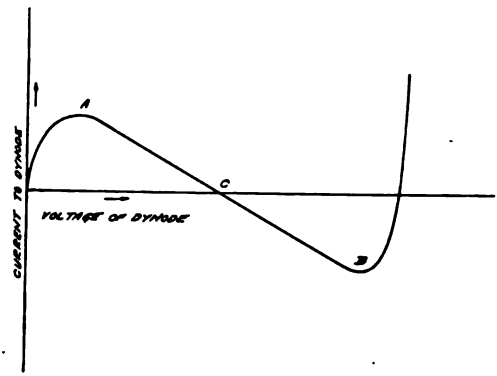

FIGURE 4—Ideal volt-ampere characteristic of dynatron

(*C*, Figure 4). This potential may most conveniently be obtained as shown, from a high resistance potentiometer (20,000-100,000 ohms) between the anode battery and ground. The circuit *L*, *C* is tuned to approximately the signal frequency, and generates continuous waves by virtue of the negative resistance of the dynode-anode circuit. It was shown in a previous paper,[2] that these oscillations are always maintained providing the ratio L/C of inductance to capacity is greater than the product of the negative resistance by the resistance of the tuned circuit. These radio frequency oscillations pass thru the telephones as capacity current, or may be by-passed by a small condenser in multiple with the telephones. Their rectified component passes thru the telephone windings and produces audible effects. It will be shown later that the action of the signal is to produce rectification of these local dynatron oscillations, without changing their amplitude.

[1]Previous citation, page 18.

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The process of operating the detector consists simply in varying the frequency of the dynatron oscillations by means of the variable condenser C until it is approximately equal to the signal frequency, as evidenced by an audible note, and then increasing the intensity and purity of this note by tuning the input circuit in the usual way.

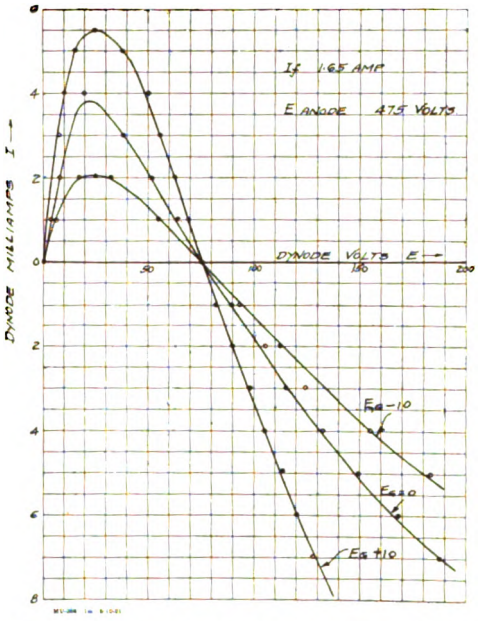

FIGURE 5—Experimental volt-ampere characteristics of pliodynatron at three different grid voltages

The detector action may be seen from Figure 8, which gives the volt-ampere characteristics of the pliodynatron at three different grid voltages (reproduced from Figure 5).

A. No Signal

The curve marked e_o represents the characteristic at normal grid voltage, with no signal impressed. If the ratio of inductance to capacity in the dynode circuit is appropriate, that is, only slightly in excess of that necessary for oscillations, the dynode oscillates symmetrically over the straight portion of this curve, between voltage limits represented by E_- and E_+. The average voltage during oscillation is E_o, and the average current per cycle,

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if E_o is the voltage at which the curve crosses the axis, is zero. This is the current that flows thru the telephones. Since e_o may be any grid voltage, it follows that the current thru the telephone windings is identically zero *for all grid voltages, including varying grid voltages of any frequency except signal frequency.* Hence all audio frequencies impressed on the grid, including those produced by alternating current in the filament, and all radio frequencies, except those within heterodyne range of the local oscillations, produce no effect whatever in the telephones. This fact has been carefully checked by experiment.

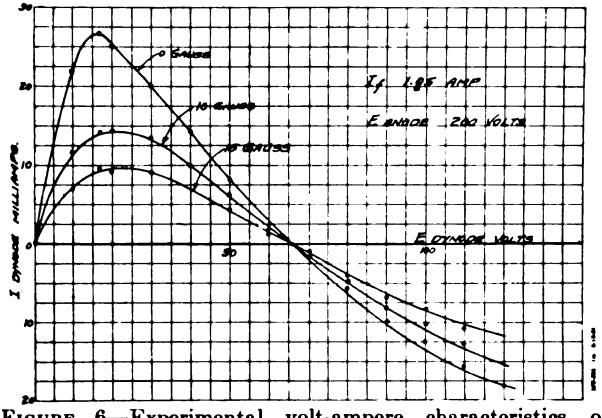

FIGURE 6—Experimental volt-ampere characteristics of magnetically controlled dynatron for three different magnetic fields

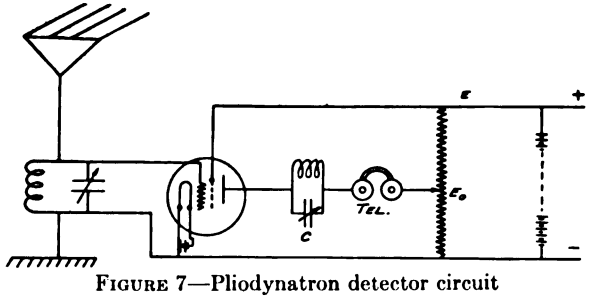

FIGURE 7—Pliodynatron detector circuit

In order to obtain complete silence from interfering signals, the three conditions mentioned above must be fulfilled: viz. (1) The volt-ampere characteristic must be straight; (2) the dynode voltage E_o must be that at which the dynode current is zero; (3) the amplitude of oscillation must be small, which requires proper ratio of inductance to capacity and resistance. In

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practice, however, considerable variations from these ideal conditions may be made without appreciable disturbance.

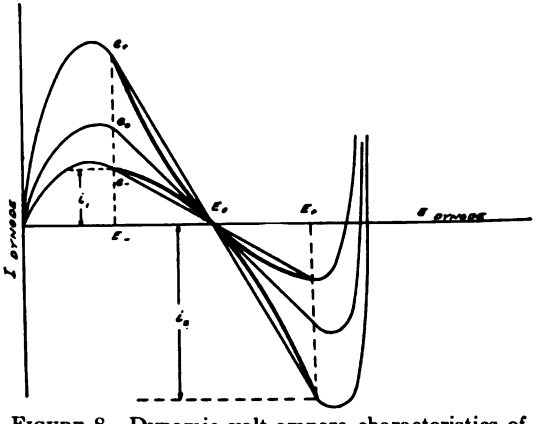

FIGURE 8—Dynamic volt-ampere characteristics of pliodynatron detector with impressed signal

B. SYNCHRONOUS SIGNAL

The effect of a signal of the same frequency as the local oscillation is unique. Referring to Figure 7, let continuous waves of the same frequency as the local oscillations be impressed on the grid, and let e_+ and e_- be the maximum and minimum values of the alternating grid voltage. The dynode volt-ampere characteristics corresponding to these grid voltages are represented in Figure 8 by the curves marked e_+ and e_-. If the phase relation is such that the grid voltage is e_- when the dynode is at its most negative value E_-, the instantaneous dynode current will be represented by the ordinate i_1. Half a cycle later the dynode voltage will be E_+, but the grid will now be at its most positive voltage e_+, and the instantaneous current will be the value i_2 on the e_+ curve. The volt-ampere characteristic corresponding to this condition of operation *with synchronous signal* will therefore be that given by the lower heavy curve. The average current is no longer zero, but has a definite negative direct current value, proportional to the amplitude of the signal. If the signal is modulated by voice frequency, the current in the telephones will be a true reproduction of the voice current. This has been checked by experiment and oscillograms.

C. SLIGHTLY ASYNCHRONOUS SIGNAL

If the frequency of the local oscillation, instead of being exactly synchronous with the signal, is slightly different, the

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current at any time will be the same as in the case of exact synchronism described above; but the relative phases of grid and dynode will slowly change until the grid is at e_+ when the dynode is at E_-. The volt-ampere characteristic will then be that represented by the upper heavy curve, and the average current will be positive. These positive and negative average currents will follow each other at a frequency equal to the difference between the frequencies of signal and local oscillation, producing an audible note in the telephones. It will be shown later, both by mathematical analysis and oscillograms, that this note is a pure sine wave of frequency equal to the difference between signal and local oscillation, the only other currents present being of radio frequency, namely, the local oscillation and a frequency equal to the sum of local oscillation and signal.

In Figure 8, it is assumed that the *amplitude* of the dynode voltage oscillations is not changed by the signal. The justification for this assumption is two-fold:

(a) It is required by the theory of operation. The time average, over a signal frequency cycle, of negative conductance, and hence the average negative damping co-efficient of the dynode voltage oscillation, is constant and equal to its value when there is no signal (compare equation (13) below). This negative damping is a measure of the power fed into the oscillating circuit and hence of the amplitude of the oscillations. The stored energy in the local oscillating circuit, L, C, is very large, so that its change during a single cycle is inappreciable. It is, therefore, to be expected that the amplitude of the local oscillations, and consequently of the voltage at the terminals of the oscillating circuit, which is the dynode voltage, will be constant.

(b) It is shown to be true by the oscillograms, and the operating characteristics based upon it agree with the experimental tests. The oscillograms, Figures 10 to 13, show only extremely slight variations in the amplitude of the current in the oscillating circuit, even when the signal is so strong that the telephone current is completely rectified. These signals are many times stronger than those used in radio, and the slight changes in amplitude of oscillation are completely accounted for by the departure from linear amplification at these large grid amplitudes. The dynode voltage amplitude is equal to the product of this oscillating current by the impedance of the coil L.

In the case of synchronous signal the oscillograms (Figures 21 to 26) show a considerable increase in amplitude when the signal is impressed, but this is due to the unsymmetrical operating conditions, as will be discussed later.

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The operation of the magnetically-controlled dynatron is identical with that of the pliodynatron, except in the method of applying the control power of the signal. In the magnetically-controlled detector the antenna coil surrounds the dynatron[3]

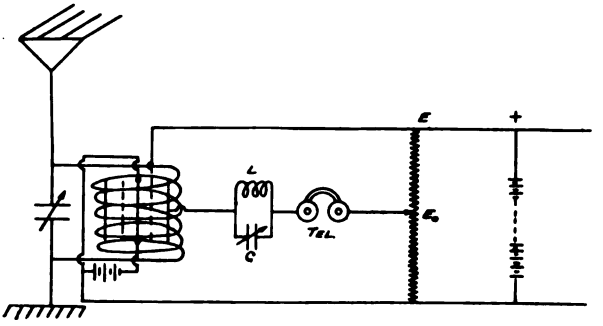

FIGURE 9—Circuit of magnetically-controlled detector

as shown in Figure 9, and the *magnetic field* of this coil is used for control; in the pliodynatron detector the *electrostatic field* between the ends of this coil is used for control. The sensitiveness of the magnetic control was slightly less than that of the electrostatic (pliodynatron) in the tests that we made, but the difference was so small as to indicate that if the tube and circuit were as well developed as those of the pliodynatron the sensitiveness of the two would be identical. The operating characteristics of the magnetically-controlled detector are identical with those of the pliodynatron, as shown by the oscillograms (See Figure 13).

OSCILLOGRAPHIC TESTS OF HETERODYNE OPERATION

In order to test the theory of detector action described above, an audio frequency model of the circuit shown in Figure 7 was constructed, in which the telephones were replaced by the vibrator of an oscillograph. Other vibrators were inserted in the oscillating circuit, the anode circuit, and the input signal circuit; so as to record the frequency, phase, and wave-shape of the dynode or telephone current, the circulating current in the tuned circuit, the anode current, and the signal voltage. The latter was a sine wave of from 5 to 10 volts amplitude, obtained by tapping off the voltage drop between two points on a fine wire resistance in the output circuit of a pliotron oscillator.

Figure 10 shows the currents in the dynode, anode, and tuned

[3]Electrostatic capacity reactions between coil and dynode were prevented by covering the tube, except for a narrow gap, with grounded tin foil or sheet copper. The control coil was either wound directly on this foil, or wound on a form that fitted loosely over it.

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circuits when no signal is impressed. The only thing to be noted is that the dynode or telephone current is symmetrical and constant with respect to its zero line. It is not a perfect sine wave, but this does nor affect the conclusions to be drawn. This film was taken with the magnetically controlled dynatron. An exactly similar film was obtained with the pliodynatron with no signal.

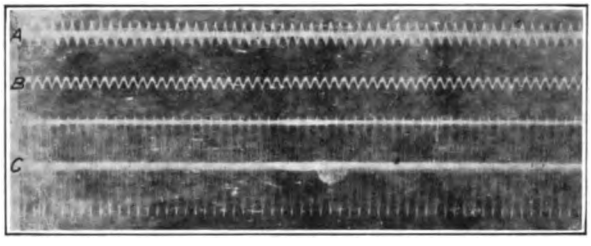

FIGURE 10—Oscillographic test of magnetically-controlled detector with no signal (frequency = 1,500 cycles)
Curve A—Current in dynode (telephone) circuit
Curve B—Current in anode circuit
Curve C—Current in tuned circuit

Figure 11 shows the effect of a signal impressed upon the grid of the pliodynatron. *The dynode high frequency current remains unchanged in amplitude, but its average value varies sinusoidally between complete rectification in the positive direction and complete rectification in the negative direction.* The anode current shows the same rectified components, in opposite phase. This was necessary, since all electrons lost by the dynode go to the anode. The current in the tuned circuit (lower curve), on the other hand, shows very little change in amplitude, which justifies the assumption of constant amplitude of dynode voltage oscillation referred to above.

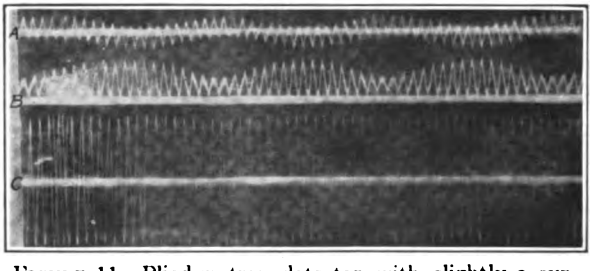

FIGURE 11—Pliodynatron detector with slightly a synchronous signal (heterodyne operation)
A—Telephone current
B—Anode current
C—Circulating (tuned circuit) current

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The "snake frequency," as it may be called, is the difference between signal and local oscillation frequencies. This may be verified by measurements on Figure 12, in which the anode current is omitted and the signal voltage recorded (lower curve.) The constancy of the current amplitude in the tuned circuit, as evidence of the constancy of dynode voltage amplitude, is again to be noted.

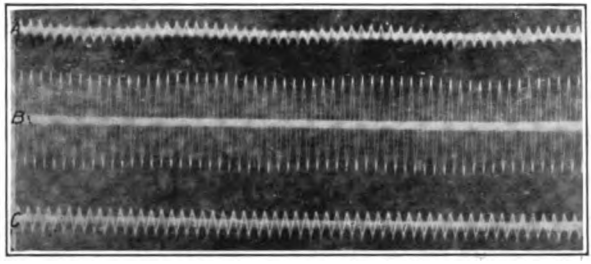

FIGURE 12—Pliodynatron detector in heterodyne operation, showing signal voltage

A—Telephone current
B—Circulating current
C—Signal voltage

Figure 13 shows the corresponding behavior for the magnetically-controlled dynatron. The upper curve is the dynode current, modulated by the signal; the middle curve is the signal *voltage*, that is, the voltage at the terminals of the control coil, which is wound around the tube (Figure 9). The controlling *magnetic field* is 90 degrees out of phase with this control voltage, as is very evident in the oscillograms of Figures 14 to 17. The lower curve is the circulating current. The characteristics are the same as for the pliodynatron.

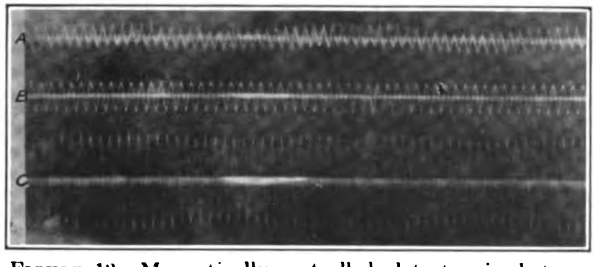

FIGURE 13—Magnetically-controlled detector in heterodyne operation

A—Telephone current
B—Signal voltage
C—Circulating current

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Figures 14 to 17 show the effect of signal frequencies which are not near the frequency of the local oscillation. These films were taken with the magnetically-controlled dynatron.

Figure 14 shows the effect of a 40 cycle signal of approximately the same amplitude as the signals in Figures 11 to 13. The modulation of the amplitude of the oscillating current is clearly shown, and the dynode current is probably modulated in the same ratio; but there is no sign of rectification.

Figure 15 shows the effect of a much larger 40 cycle signal producing complete modulation of the dynode current. Here the dynode current is slightly distorted, owing to the asymmetric amplification, but even in this extreme case there is very little rectification. Figures 16 and 17 show the effect of signal fre-

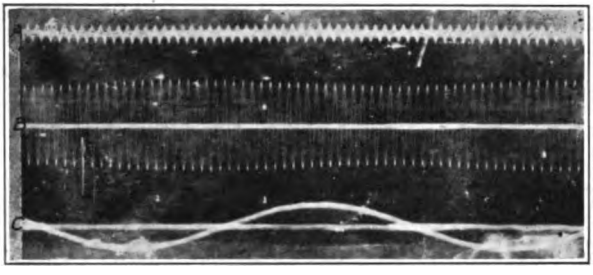

FIGURE 14—Magnetically-controlled detector oscillating at 1,500 cycles with moderate 40 cycle signal

A—Telephone current
B—Circulating current
C—40 cycle voltage

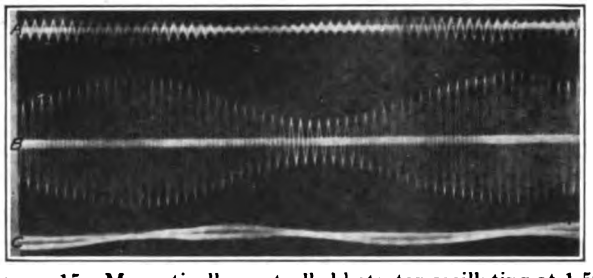

FIGURE 15—Magnetically-controlledd etector oscillating at 1,500 cycles with large 40 cycle signal

A—Telephone current
B—Circulating current
C—40 cycle voltage

quencies approximately 1/7 and 1/4 of the dynatron frequency. The dynode current is perfectly symmetrical, with no sign of rectification, in spite of complete modulation. These results,

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showing the absence of rectification except at synchronous frequency, are completely in accord with the theory of operation outlined above, and with the mathematical analysis which follows.

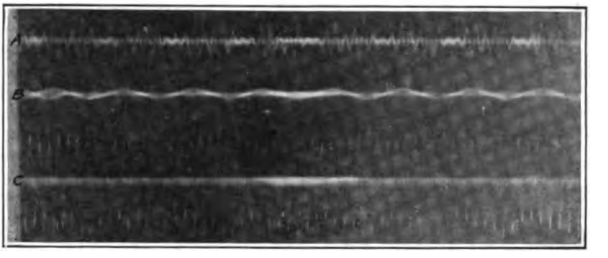

FIGURE 16—Magnetically-controlled detector oscillating at approximately 1,500 cycles with 250 cycle signal
A—Telephone current
B—Signal voltage
C—Circulating current

Oscillographic tests of purely synchronous operation are shown in Figures 21 to 26, and are equally in accord with the theory. Before discussing them, however, the mathematical analysis will be briefly outlined.

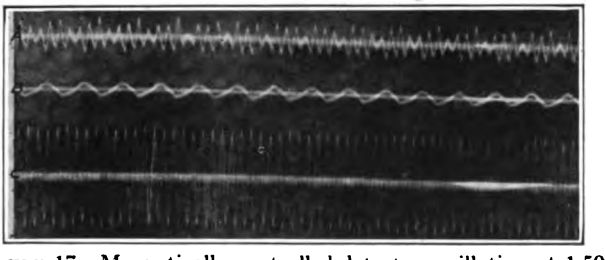

FIGURE 17—Magnetically-controlled detector oscillating at 1,500 cycles with 500 cycle signal
A—Telephone current
B—Signal voltage
C—Circulating current

MATHEMATICAL ANALYSIS

The analysis will be applied specifically to the pliodynatron. The same analysis will hold for the magnetically-controlled dynatron if magnetic field is substituted for grid voltage.

The circuit is shown again in Figure 18. In order to simplify the analysis, the effect of the inductance of the telephones will be neglected for the present. The results will then be applicable to oscillographic tests, and to audible operation with low

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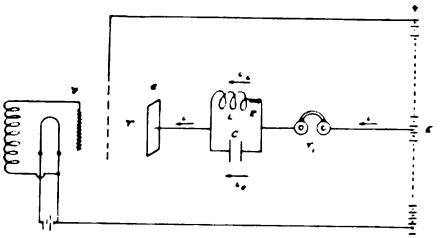

FIGURE 18—Circuit of pliodynatron detector

impedance telephones, or with a pure resistance output circuit working into a pliotron amplifier. In practice it is found that the inductance of the telephones has no noticeable effect on the operation until its ratio to distributed capacity approaches the value sufficient for sustained oscillations. Resistance in the dynode circuit has no effect except to reduce by that amount the negative resistance of the circuit, as has been shown in the previous paper already mentioned. This resistance will be included in the general solution (Equation 8.)

The operation is completely determined by the constants of the circuit and the two electrical characteristics of the pliodynatron, namely:

(a) NEGATIVE RESISTANCE

This is defined empirically from the volt-ampere characteristic as the slope of the volt-ampere curve (Figure 19):

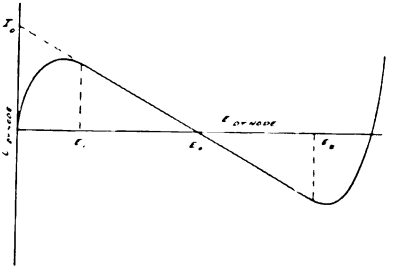

FIGURE 19 Volt-ampere characteristic of pliodynatron at constant grid voltage

$$r = \frac{\partial e}{\partial i} = -\frac{E_a}{I_a}; \quad F_1 < e < E_2 \tag{1}$$

The positive current from the dynode thru the vacuum is then given by the experimental characteristic (Figure 19) as

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$$i = I_o - \frac{e}{r} \tag{2}$$

where r is the positive numerical value of the negative resistance.

(b) Grid Control Constant

This is defined in the pliotron as

$$g = \frac{\partial i_p}{\partial e_g}$$

where e_g is the control grid voltage and i_p the anode current at constant voltage. In the case of the pliodynatron only a small part of the current represented by i_p strikes the anode. The rest, a nearly constant fraction, passes thru the anode to the dynode, and is represented by the current of primary electrons, I_o, which strikes the dynode. Hence the grid control characteristic of the *primary* dynode current will be similar (Figure 20) to that of the pliotron, and the corresponding control constant may be defined as

$$g^d_{\text{dynode}} = \frac{\partial I_o}{\partial V_g} \tag{3}$$

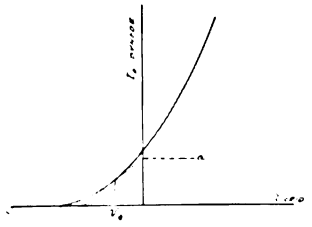

Figure 20—Grid-control characteristic of pliodynatron

The primary dynode current may then be represented, for small amplitudes of grid voltage, by the linear equation

$$I_o = a + g\,v \tag{4}$$

This equation holds with sufficient accuracy for all operating conditions, since the anode voltage is always constant and the signal amplitude small.

A. Dynode Oscillations with no Signal

It will be convenient to derive first the equation for the dynode oscillation when no signal is impressed.

Referring to Figure 18, the electrical behavior of the circuit is defined by Equation 2 above, together with the three following equations:

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$$R\,i_L + L\frac{d}{dt}(i_L) = E - i\,r_1 - e \tag{5}$$

$$i_c = C\frac{d}{dt}(E - i\,r_1 - e) \tag{6}$$

$$i = i_L + i_c \tag{7}$$

Elimination of i, i_L and i_c between these four equations gives, as the differential equation of the circuit when no signal is impressed:

$$\frac{d^2e}{dt^2} + \left[\frac{R}{L} - \frac{1}{C(r-r_1)}\right]\frac{de}{dt} + \frac{1}{LC}\left(1 - \frac{R}{r-r_1}\right)e + \frac{I_o(R+r_1) - E}{\frac{LC(1-r_1)}{r}} = 0 \quad \cdots \tag{8}$$

The solution of which if $\left[\frac{R}{L} - \frac{1}{(r-r_1)C}\right]^2 - \frac{4}{LC} < 0$, is

$$e = E_o + \frac{E - E_o}{1 - \frac{R+r_1}{r}} + A\varepsilon^{-\frac{1}{2}\left[\frac{R}{L} - \frac{1}{(r-r_1)C}\right]t} \sin\left[\sqrt{\frac{1}{LC} - \left(\frac{R}{2L} + \frac{1}{2C[r-r_1]}\right)^2}\,t - \alpha\right] \tag{9}$$

where A and α are arbitrary constants representing amplitude and phase, respectively, at the time $t=0$; and E is the impressed dynode voltage, which need not be the voltage E_o at which the dynode characteristic crosses the axis (Figure 19).

This solution represents a sine wave oscillation of dynode voltage, which will die out, continue unchanged, or increase indefinitely in amplitude according as the damping factor, which is the multiplier of t in the exponential term, is positive, zero, or negative. The case under consideration is that in which the damping is slightly negative, so that continuous stable oscillations are maintained. It is evident that the amplitude cannot increase indefinitely, since the constant value r of the negative resistance which Equation 9 assumes is limited to the range of voltage represented by $E_1 \ldots E_2$ (Figure 19). Beyond the range $E_1 \ldots E_2$ the resistance is positive, so that oscillations of greater amplitude are strongly damped.

The frequency of oscillation is slightly lowered by the negative resistance, as represented by the parenthesis $\left(\frac{R}{2L} + \frac{1}{2(r-r_1)C}\right)^2$ under the radical. This is the same as the damping coefficient, with the sign between the terms changed. When the damping

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coefficient is small, which is the condition for best operation, these two terms must be approximately equal. Hence the frequency correction due to resistance is approximately 4 times that of the freely oscillating tuned circuit. This is of the order of one part in one million in radio frequency circuits.

B. Dynode Oscillation with Signal Impressed on Grid

The effect of varying grid voltage is to vary the value of I_o (Figure 19) according to Equation 4, and hence the negative resistance (Equation 1). Substituting the values of r and I_o from Equations 1 and 4, Equation 2 becomes

$$i = (a + g\,v)\left(1 - \frac{e}{E_o}\right) \tag{10}$$

Let the signal voltage impressed on the grid be a sine wave of frequency ω and amplitude V, so that

$$v = v_o + V \sin \omega t \tag{11}$$

Equation 2 then becomes

$$i = [a + g\,v_o + gV \sin \omega t]\left[1 - \frac{e}{E_o}\right] \tag{12}$$

Combining Equation 12 with Equation 5, 6, and 7, and elim inating i, i_c, and i_L, one easily obtains the differential equation for dynode voltage when a signal is impressed on the grid:

$$\frac{d^2e}{dt^2} + \left[\frac{R}{L} - \frac{1}{CE_o}(A + g\,v_o + gV \sin \omega t)\right]\frac{de}{dt} + \frac{1}{LC}\left[1 - \frac{R}{E_o}(a + g\,v_o + gV \sin \omega t) - \frac{L\,gV\omega}{E_o}\cos \omega t\right]e + \frac{R}{LC}(a + g\,v_o + gV \sin \omega t) + g\frac{V\omega \cos \omega t}{C} - \frac{E}{LC} = 0 \tag{13}$$

This equation is probably soluble. An exact solution is unnecessary for the present purpose, however, as a simple approximation will cover the operating conditions under discussion.

Comparing Equation 13 with Equation 8, remembering[4] that $r_o = \frac{E_o}{a + g\,v_o}$, it is seen that the co-efficient of e, which represents the damping factor, is the same in both cases except for the term $g\,V \sin \omega t$. This term, which represents the amplitude of the signal voltage, is always small compared with $(a + g\,v_0)$ and *its average value is zero.* A signal whose frequency, ω, is low compared with the frequency of the dynatron oscillations will therefore produce small periodic variations, of frequency ω,

[4]In order to shorten Equation 13, the telephone resistance r has been taken as zero. Its effect is purely additive, as in Equation 8, and all the above conclusions hold if it is included.

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in the amplitude of the dynode voltage oscillations, and hence of the current in the tuned circuit, which is proportional to dynode voltage. This is shown for a very large signal (compared with radio signals) in Figure 14, and for enormous signals in Figures 15 to 17. For signal frequencies equal to or higher than the dynatron frequency, however, the inertia of the tuned circuit prevents its response to these rapid variations in damping, and only the average value of the damping factor is effective. This is the same as when there is no signal. Hence these radio frequency signals will have no effect upon the amplitude of dynode voltage oscillation. The same argument applies to the average value of dynode voltage, represented by the constant term in Equation 9.

As regards the effect of the coefficient in the third term of Equation 13 on the frequency,[3] it is easily verified that for normal signals the variable part of this coefficient is of the same relative magnitude as $\frac{R}{r-r_1}$, in Equation 8, which has been shown to affect the period by only about one part in one million. For very strong signals, the last member in the parenthesis of this coefficient becomes appreciable, and produces a "synchronizing effect" between the signal and the local oscillating circuit, which is of importance in "zero beat" reception. The correctness of these conclusions both as to frequency and synchronizing effect can be verified from the oscillograms shown in Figures 21 to 26.

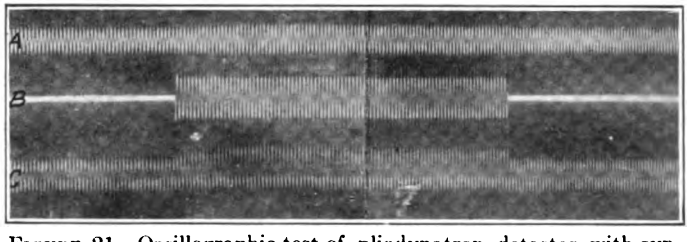

FIGURE 21—Oscillographic test of pliodynatron detector with synchronous signal (zero beats)
A—Circulating current
B—Signal voltage
C—Telephone current

Equation 9 may therefore be taken as a sufficiently accurate solution of (13) under the conditions of operation.

C. DYNODE CURRENT WITH SIGNAL IMPRESSED ON GRID

The dynode current is obtained by substituting the value

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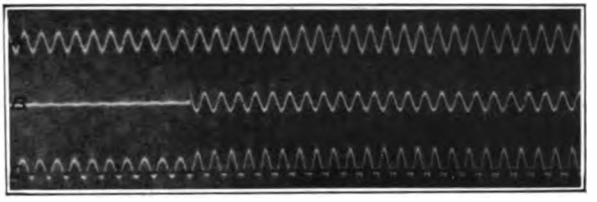

FIGURE 22—Pliodynatron detector with synchronous signal. Signal applied in phase

A—Circulating current
B—Signal voltage
C—Telephone current

of e from Equation 9 in Equation 12. Writing A' and $\frac{\omega_o}{2\pi}$ for the amplitude and frequency of the oscillation in Equation 9, namely,

$$e = E_o + \frac{E - E_o}{1 - \frac{R + r_1}{r}} + A' \sin(\omega_o t - a) \quad \cdots \quad (g')$$

and writing r_0 for the normal negative resistance (with no signal), one thus obtains, from (9′) and 12).

$$\underset{\leftarrow\text{Direct Current Component}\rightarrow}{i} = \frac{E - E_o}{r_o\left(1 - \frac{R + r_1}{r_o}\right)} + \underset{\leftarrow\text{Dynatron Frequency}\rightarrow}{\frac{A'}{r_o} \sin(\omega t - a)}$$

$$+ \underset{\leftarrow\text{Signal Frequency}\rightarrow}{\frac{E - E_o}{E_o\left(1 - \frac{R + r_1}{r_o}\right)} g V \sin \omega t} + \underset{\leftarrow\text{Difference Frequency}\rightarrow}{\frac{A' g V}{2 E_o} \cos([\omega - \omega_o]t - a)}$$

$$\underset{\leftarrow\text{Double Frequency}\rightarrow}{- \frac{A' g V}{2 E_o} \cos([\omega + \omega_o]t - a)} \qquad (14)$$

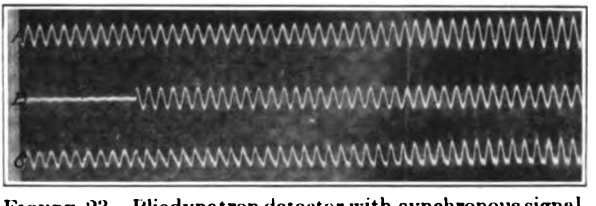

FIGURE 23—Pliodynatron detector with synchronous signal. Signal applied 180° out of phase

A—Circulating current
B—Signal voltage
C—Telephone current

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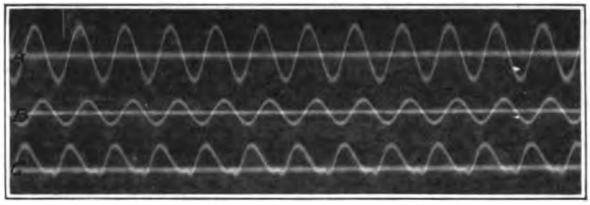

FIGURE 24—Pliodynatron detector in synchronous operation. Signal frequency lower than normal pliodynatron frequency
A—Circulating current
B—Signal voltage
C—Telephone current

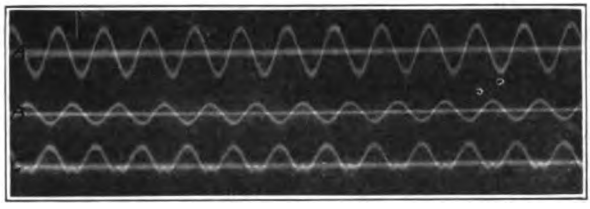

FIGURE 25—Pliodynatron detector in synchronous operation. Signal exactly in synchronism
A—Circulating current
B—Signal voltage
C—Telephone current

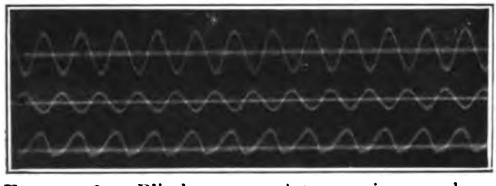

FIGURE 26—Pliodynatron detector in synchronous operation. Signal frequency higher than normal pliodynatron frequency
A—Circulating current
B—Signal voltage
C—Telephone current

It is seen that the dynode current contains, in general, a constant direct current component, the dynatron oscillation, a signal frequency component, a difference frequency or heterodyne component, and a component which is the sum of signal and local oscillation. If the impressed dynode voltage is the voltage E_o at which the dynode characteristic crosses the axis (Figure 19), both the constant term and the signal frequency component are zero. The dynode current, which is the current thru the telephones, contains then only the dynatron oscillation and

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the sum and difference of the dynatron and signal frequencies. There is no rectification and no direct current component. Hence, unless the difference frequency is audible, there will be no audible sound in the telephones, even when the signal is modulated or interrupted. This conclusion holds, of course, only for signal amplitudes for which the assumption of linear grid amplification is justified.

In the case of exact synchronism between local oscillation and signal the difference frequency disappears, or rather becomes a direct current component the amplitude of which is proportional to that of the signal. Besides this direct current component there remains, if $E = E_o$, only the dynatron sine wave and its second harmonic. This is clearly shown in the following oscillograms. (Figures 21 to 26.)

Oscillographic Tests of Synchronous Operation

As a further test of the theory of operation outlined above, oscillographic tests were made with a pliodynatron oscillating at low frequency, with a synchronous signal, obtained from a pliotron oscillator, impressed on the grid. In order to obtain large dynode currents for the oscillograph, the anode voltage was raised so high that the dynode characteristic was considerably distorted, being much longer on the negative side (below the axis) than on the positive, and considerably curved. The result was that it was not practical to operate at dynode voltage E_0, so that the average dynode current was not zero; and the amplitude of the current in the oscillating circuit increased considerably when the signal was applied, owing to the curvature of the characteristic. In spite of this the dynode current curves show very well the characteristic features predicted by Equation 14, namely, the direct current component and the second harmonic. In each film the upper and lower curves are the currents in the tuned circuit and dynode (telephone) circuit, respectively, and the middle curve the signal voltage. The signal amplitude was from 5 to 10 volts. This is, of course, large compared with normal signals.

Figure 21 shows a typical signal dash. The dynode current is increased slightly in amplitude and raised bodily, producing a direct current component of current in the telephones.

Figure 22 is a lower frequency, and shows clearly the sine wave form of the dynode current before the signal is impressed, and the second harmonic after the signal is impressed. In this case, the signal and dynode happened to be in exactly

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the same phase at the instant when the signal was impressed on the grid, so that only 3 or 4 cycles were required to build up the rectification and the new wave form. In general, from 10 to 20 cycles are required, and the number might be much larger in the case of a very weak signal.

Figure 23 shows a case in which the signal was just 180° out of phase with the dynode current at the instant it was applied. The distorting effect of the signal is evident at once, but it is only after 30 cycles that the dynatron oscillation is finally pulled into phase and shows its characteristic features.

Figures 24, 25, and 26 show the effect of a slight difference in frequency between the signal and the local oscillation. The synchronizing force of the signal is sufficient to hold the dynatron in synchronism, but a marked distortion of the dynode current is produced. In Figure 24 the signal frequency is slightly lower than that of the dynatron; in Figure 25 the two are exactly equal, and in Figure 26 the signal is higher. The second harmonic is clearly shown in Figure 25.

Remarks on Operation

Operation of the pliodynatron as heterodyne receiver has given the following results:

(a) The detector action is reliable and reproducible.

(b) The sensitiveness is the same as that of separate heterodyne or normal self-heterodyne. By adjusting the ratio of inductance and capacity of the telephones, so as to utilize negative resistance amplification in the telephones, the sensitiveness can be increased to the limit obtainable by regeneration in self-heterodyne.

(c) The operation is the same whether the filament is heated with alternating or direct current, and no noise due to the alternating current can be detected when the dynode voltage is properly chosen.

(d) No signal can be detected by a circuit coupled to the oscillating circuit of the pliodynatron, even after rectification by a pliotron detector. This proves the absence of signal frequency in the oscillating circuit, that is, the absence of modulation of the amplitude of local oscillations by the signal, thus confirming the conclusions of the mathematical analysis and the oscillograms.

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(e) The stray ratio is superior to that of ordinary rectifying heterodyne detectors.

Research Laboratory,
General Electric Company,
Schenectady, New York,
February 3, 1922.

SUMMARY: The dynatron is a tube having a filament, an anode, and a supplementary anode called a "dynode." The tube operation is based on the secondary emission of electrons from the anode. Its use as an oscillating detector for heterodyne reception is described, and the mathematical theory of its operation is given. The theory is verified experimentally with oscillographic illustrations.

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APPLICATION TO RADIO OF WIRE TRANSMISSION ENGINEERING*

By

Lloyd Espenschied

(Department of Development and Research, American Telegraph and Telephone Company, New York)

One of the most interesting aspects of the development of radio during the last few years, and particularly of radio telephony, is the obvious convergence of its technique with that of wire transmission. It is, of course, the advent into both of these arts of that remarkable device, the electron tube, which is responsible for the close technical relations which now exist between them.

This community of interest, however, altho thus greatly stimulated by a device of such range of utility as to find important applications in both arts, is not due primarily to any device *per se*, but rather to the fact that both type of systems are subject fundamentally, as communication systems, to the same general requirements and design considerations concerning their intelligence-carrying capabilities. These underlying communication requirements lead to similar considerations in both types of systems as to the efficiency and fidelity with which the transmission of intelligence is effected and give rise to a transmission background, as it were, which is common to both arts.

The engineering handling of the transmission problems, which arise from these fundamental communication requirements, has been quite highly developed in the older of the two arts—wire transmission—in connection with telephone repeaters and carrier telephone and telegraph systems. It should be, therefore, interesting and profitable to apply some of the transmission technique thus developed in the wire art to several of the more important radio problems. In so doing, we obtain rather new viewpoints of radio transmission and a useful correlation of it with the better established wire methods. It is hoped, therefore, that the picture which is presented of radio and wire transmission, treated from a common standpoint, may con-

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tribute to a better appreciation of both arts by radio and wire engineers alike and may make clear the underlying transmission principles which are common to them.

Principal among the problems of electric communication is the one of delivering at the receiving end the required volume of signal with the necessary freedom from interference. The delivering of the required volume is a matter of controlling the transmission losses and the amplification of the system; while the obviating of interference is, of course, concerned with the reduction of the ratio of the interfering to the signaling energy.

Transmission Losses

In considering these factors we will take up first the primary one of the losses which are suffered by the carrier waves as they are propagated thru the transmission medium. In both wire and radio transmission, of course, the actual propagation of the electromagnetic wave energy occurs in the "ether," the difference being that in the wire case, the waves are bound to a guiding path, whereas in the radio case they are transmitted freely in all directions and bound merely to the earth's surface. This difference in the mechanism of transmission gives rise to an important difference in the transmission losses occurring in the two cases. In order to assist in visualizing the two cases they are indicated diagrammatically in Figure 1.

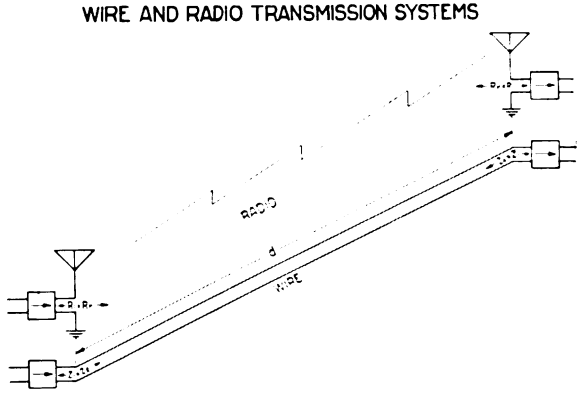

Figure 1

Referring first to the wire case, the law in accordance with which the current and voltage strength decrease as the trans-

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mission wave travels along the wire, is the familiar one of attenuation.

$$I_1 \varepsilon^{-\alpha l} = I_2 \qquad (1)$$
$$E_1 \varepsilon^{-\alpha l} = E_2$$

which simply expresses the fact, that as the wave proceeds along the wire, the losses in the resistance of the conductor and in the insulation, extract for each mile a certain definite proportion of the voltage and current which arrives at that point. After traveling (l) miles the original current I_1 is attenuated down to a value $I_1 \varepsilon^{-\alpha l}$ which represents the received current I_2. This is the same general law of damping as applies to the dying down of the voltage and current in an oscillation circuit, except that here the damping is with respect to distance along the line rather than time. We are assuming, of course, that the circuit is so terminated as to avoid reflection effects at the terminals—a condition readily met, by making the terminal impedance equal to the characteristic line impedance. This is indicated in the figure by the designations, Z (internal) equals Z (line). A similar relation is taken for the radio case. The "line" impedance is here the antenna radiation resistance while the "terminal" impedance is the resistance internal to the antenna and the apparatus, assuming resonance; thus R (internal) equals R (radiation).

We know that in radio there are two distinct causes of the transmission loss: (1) that due to the spreading out of the waves, which is characteristic of non-guided wave transmission; and (2) that due to absorption in the air and earth's surface, which extracts a definite percentage loss for each mile of the radio circuit and which conforms, therefore, to an exponential law similar in its general nature to that of wire attenuation.

This transmission law, as expressed by the familiar Austin-Cohen formula, is given in the appendix.[1] In order to express the radio transmission loss in some general manner which will be comparable to the expression of wire transmission loss, these conditions have been taken for the radio case:

(1) That we will use as the measure of the transmission loss the ratio of the square root of the power radiated from the sending antenna to the square root of the power delivered in the receiving antenna. This is, of course, the same criterion as is used for wire transmission.

[1] Measurements on ship-shore transmission made since the above was written, indicate that the Austin-Cohen law holds quite well for frequencies as high as about 1,000,000 cycles.

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(2) The radiation resistance of the two antennas, sending and receiving, are made equal, analogous to the equality of line impedance at the two ends of the wire system.

(3) Also the internal antenna resistance, which corresponds to the terminating impedance in the wire case, is made equal to the radiation resistance for both ends. This is the condition of maximum power transfer between the "line" and the terminal.

These assumptions set up the two cases, radio and wire, on a comparable basis and facilitate a comparison of them. They are favorable to radio in that *they do not take account of practical limitations which obtain in antennas.* The radio curves below should be read, therefore, as giving the minimum possible losses for daylight transmission over water.

These curves show the manner in which the transmission loss varies with distance, for various frequencies, for both radio and wire. The ordinates are plotted in terms of the logarithm of the ratio of the sent to the received currents, or voltages, in circuits of equal impedances. In so doing we are plotting the losses on the straight attenuation basis upon which they are usually plotted in the wire art; that is, the ordinates represent the exponent (αl) of the wire attenuation law, and may be directly interpreted in terms of miles of standard cable[2] by multiplying by 21. approximately. The advantage of dealing with the exponent rather than the current ratio itself is the very considerable one which is characteristic of logarithms, namely, that when thus expressed the individual losses and gains thruout a system may be summed up algebraically, and the over-all transmission equivalent of the system thus readily determined.

It should be noted that the transmission loss given in the radio curves is that obtaining between the point at which power is delivered to the ether at the sending end and that at which it is delivered to the dissipative load of the receiving antenna circuit. In Figure 1 these points are represented by R_r at the transmitter and R_i at the receiver. If at the sending end, we start with the power developed within the generator, meaning

[2] For the mile of standard cable the attenuation α (at 800 cycles) equals 0.109. Therefore the equation for current ratio, in terms of miles of standard cable, becomes

$$\frac{I_1}{I_2} = \varepsilon^{\alpha l} = \varepsilon^{0.109 \times l}$$

from which

$$l = \frac{1}{0.109} \log \varepsilon \frac{I_1}{I_2} = 21.13 \log_{10} \frac{I_1}{I_2}$$

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in R_i instead of R_r, then the power ratio is simply doubled, for the conditions assumed, and the attenuation is 0.15 or about 3 miles greater than given in the curves. The curves can be used *for obtaining the loss in any practical case* simply by taking the minimum loss as given by the curves and adding thereto the additional loss obtaining in the actual antenna.

Referring now to Figure 2—the transmission losses in the two cases are given for distances up to 200 miles (320 km.). The straight lines represent the wire losses, the bending-over curves the radio losses. Of the radio curves, the dash lines give the spreading-out losses alone, while the full lines give the total losses, including absorption.

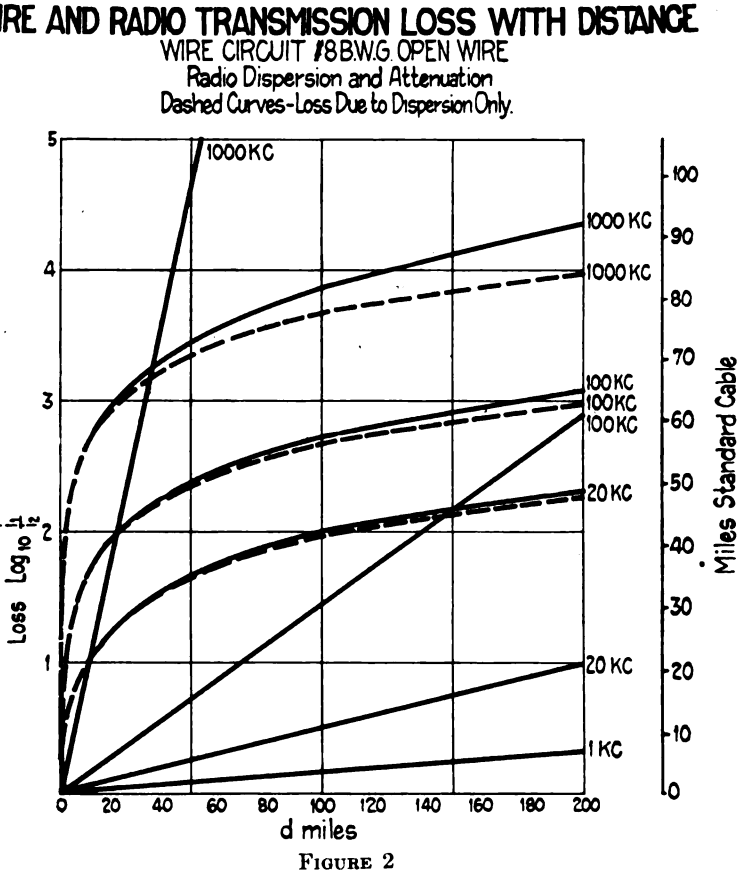

FIGURE 2

The first thing one observes is the difference in the nature of the two sets of curves—the wire losses being represented by

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straight lines, because of their exponential law and the fact that it is the logarithm or the exponent itself which is being plotted, while the radio curves jump up rapidly at first and then straighten out, in accordance with the "inverse-with-distance" law.

The second thing one notes is the fact that as a result of the large initial (or "jump off") loss, the radio values run on the whole higher than do the wire for the more usable wire frequencies and very much greater than the wire losses at telephone frequencies 1 k. c.).[3] For the wire case the number 8 Birmingham wire gauge open wire circuit is taken.[4] This is the standard long distance telephone circuit of the United States. The constants are given in the appendix.

A third characteristic which one notes in the radio curves is that the losses are greater for the higher frequencies or, conversely, lower for the lower frequencies. This is because the efficiency of the antenna has been kept constant for all frequencies. In practice the transmission losses at the lower frequencies are higher than here indicated, because of limitations in antenna heights.

Were we to take the ideal condition *as regards the transmission medium itself*, where for wires there is no conductor or dielectric loss, and for radio there is, likewise, no earth or air absorption loss, we would note: (1) that, for wires, there would be no attenuation whatever, the curve following along the X axis; (2) for radio, there would remain the loss due to dispersion, inherent in the unguided method of transmission, the magnitude of which loss is, ot course, very substantial. The dash-line radio curves show the radio losses without attenuation, the full-line curves with attenuation.

Considering the actual condition, where there is dissipative loss in the transmitting medium, we find that for moderate distances, up to 200 miles (320 km.), as plotted in Figure 2, the wire losses are in general less, and at telephone frequencies very much less, than the radio losses. The low wire attenuation at telephone frequencies is, of course, in keeping with experience and accounts for the economical terminal apparatus which is employed in telephone practice. Likewise the relatively high losses for radio accounts for the large amplification at either the sending or receiving end or both, which experience has proven to be necessary. This brings in an interesting side-light, namely, that altho in radio the transmission medium is provided by

[3] 1 k. c. is 1 kilocycle per second or 1,000 cycles per second.
[4] Diameter of number 8 Birmingham wire gauge wire = 0.165 in. = 0.42 cm.

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nature, the effective *use* of this medium is not as economical as might be expected, because it requires considerable equipment, amplifiers at both ends for overcoming the large attenuations, selective means for dividing-up frequency range and thereby "multiplexing" the ether, and antennas for getting into the medium and out again.

For the higher frequencies, the wire attenuations increase relatively more rapidly than the radio, thus limiting the frequency range which can be employed on wires without likewise running into large amplification requirements. For example, the loss at 100,000 cycles for a distance of 200 miles (320 km.), is about as great over wires as the minimum loss which it is theoretically possible to obtain over radio.

Referring now to the attenuations for longer distances, as given in Figure 3, it is of interest to note that for distances of

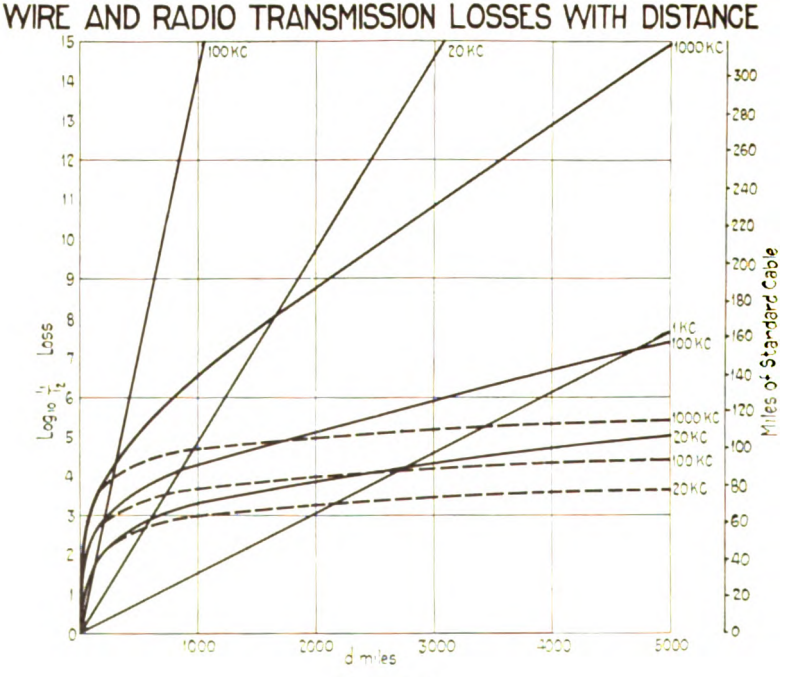

FIGURE 3

the order of 2,000 to 3,000 miles (3,200 to 4,800 km.), the lower radio frequency curves cross the 1,000 cycle wire curve, meaning that for these distances it is possible for radio transmission to be as efficient as straight telephone transmission. The wires present

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to carrier frequencies for these long distances losses which are generally greater than prevail for radio.

These attenuation relations cannot be directly converted into an economic comparison, however, for the economies depend not upon the attenuation itself, but upon, among other factors, the cost involved in *overcoming* the losses by means of amplification; and this cost in turn depends largely upon the extent to which the amplification can be applied at weak powers, as by the frequent application of telephone repeaters. By applying repeaters every few hundred miles in the wire case, the attenuation is prevented from piling up and the amplification is handled at relatively weak and therefore economical power levels. This brings us to the point of requiring that the attenuation values given above be considered in reference to the amplification and power required to overcome them and yield the necessary volume of transmission at the receiving end over and above interference.

Interference and Its Effect Upon the Transmitting Power Required

In both the radio and wire cases there is always present in the transmission medium a certain amount of stray wave energy which tends to interfere with the proper reception of the message-carrying waves. It is necessary that the communication waves arrive at the receiving end of the system with such power as to be large compared with the interfering waves—by a factor determined by the type and grade of communication involved. Inasmuch as the stray energy always has some finite value, this requirement of freedom from interference will determine, in the radio case as well as in some types of wire transmission, the minimum wave power required at the receiving end of the transmission system.

In the wire system the minimum power requirement may be expressed directly in terms of a power, or—as it is usually—a current, in the receiving apparatus, the "transfer" between the line and the receiver being a constant and efficient relation. In radio the power delivered out of the ether or "line" into the receiving antenna is so largely a function of the antenna dimensions that it is necessary to express the necessary received power in terms of the received field, usually simply as a field intensity—and not as a certain current in the terminal apparatus. Of course the transmission loss occasioned by getting from the "ether" into the receiving circuit does not affect the interference relation but

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merely the absolute amount of terminal amplification required. On the other hand the transmission loss occasioned by getting into the "ether" at the sending end affects the interference relation vitally, as we shall see.

Transmission Levels

This necessity of having to keep the power of the received waves above the interference level may be visualized by reference to Figure 4.

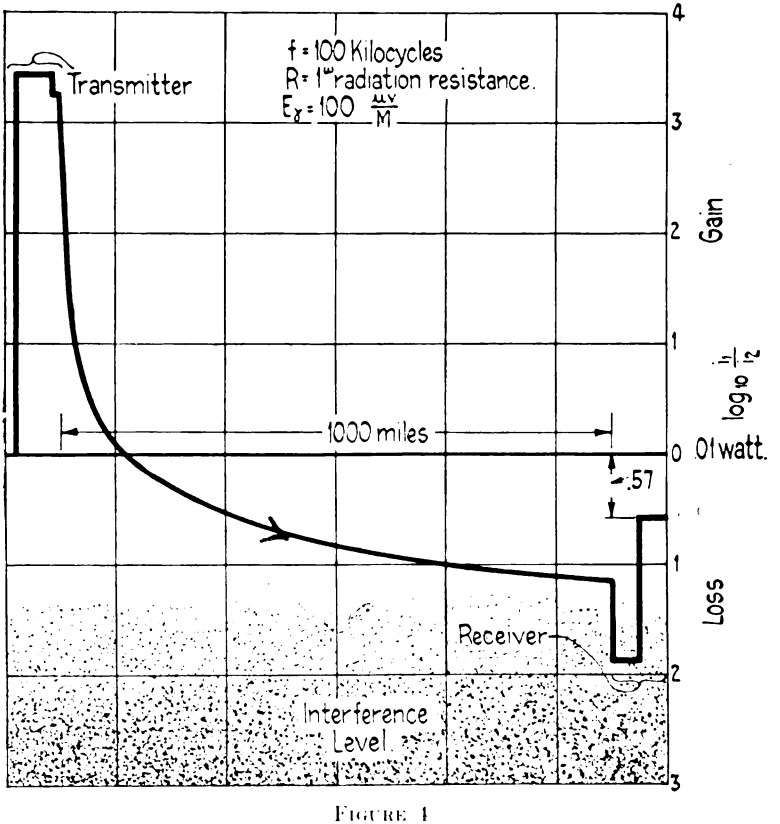

Figure 4

Here we have what in wire practice is called a "transmission level" diagram. Such a diagram is useful in showing what goes on in the system from the power and interference standpoints. The

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vertical scale is plotted in terms of the transmission level expressed as the logarithm of the current or field intensity ratios, and the horizontal scale represents progression along the system. For illustration purposes, the presence of interference is indicated at the bottom of the transmission-level scale by the shading.

Tracing thru the diagram we proceed as follows:

The point of "zero" level is taken roughly as that corresponding to the power delivered into a telephone circuit by a certain telephone transmitter when spoken into by the average talker, and is here taken to be 0.01 watt. As the voice currents are amplified to power proportions in the transmitting station, at the left, the transmission level is greatly increased, as illustrated by the vertical jump in the curve. The amplified voice currents are assumed to be converted by modulation into high frequency currents at this high power level and put into the antenna. The high frequency loss in the antenna system is indicated by the perpendicular jog in the curve. The drooping-off curve then commences, starting with a point which represents the power usefully applied to the ether in accordance with the expression I^2R, where I is the antenna current and R is the radiation resistance. The level curve falls off in accordance with the transmission loss curves previously discussed, as it extends across the transmitting medium to the receiving station. It will not do to permit the transmission level to fall as low as that of the interference, so I have shown that the transmission reaches the receiving station before dropping down very far into the interference level. At the receiving point a further transmission loss occurs in getting into the receiving antenna circuit, shown by the drop in the curve, but this loss obtains for the interference as well as the desired signals and does not affect the interference ratio. The terminal amplification brings the level up to that required for suitable audition and the difference between where this level leaves off and the original zero level, measures the overall transmission equivalent of the circuit, shown in this case as about $log_{10}\frac{I_1}{I_2}=0.57$, or about 12 miles of standard cable. This corresponds to a current ratio of about 4, a value ample for good "talk." Of course, in a one-way circuit the terminal amplification can be raised to any value desired. In a two-way circuit, however, a limit in the terminal amplification is imposed by interference between the two transmissions, as will be understood subsequently.

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We may make the following useful observations from this curve:

1. The net transmission equivalent represents the difference between the over-all loss and the over-all gain.
2. The over-all gain is divided between the transmitting and receiving ends. We should like to throw as much of this amplification as possible to the receiving end because of the economy with which amplification can be provided at low powers.
3. The extent to which we can do this, however, is distinctly limited by the fact that the transmission level obtaining at the receiving end in the transmission medium must be held above a certain amount in order to overcome interference.
4. It is, then, the absolute intensity of the interference which determines the receiving power level required, and in turn this together with the attenuation back to the transmitting station which determines the transmitting power and, in turn, the amplification required.

Thus the two transmission features most fundamentally important in the radio communication system are: (1) the interference level, and (2) the transmission loss thru the medium. These once given, the other engineering considerations follow naturally. There are analagously fundamental factors in wire communication systems. In the latter case, however, the art has advanced to a point where means of controlling the interference level are available, so that the ratio of interference to transmitted power may be made small by decreasing the former rather than increasing the latter.

Minimum Transmission Levels Obtaining in Practice

The working values which should be assumed for the ratio between the transmission level of the received signals and the interference, depend upon the type of communication involved, whether it is telephone or telegraph, for example, and upon the grade of service to be given. There is a wide difference between the transmission level which will enable telephonic signals to be barely discerned by an expert ear and that which is required for a public service communication system which must provide sufficient operating margin to enable the average person to converse with ease and certainty under all ordinary conditions.

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Under favorable static conditions, the transmission level can be permitted to fall to extraordinarily low values. When this condition is accompanied by a substantial reduction in the effective attenuation, which sometimes occurs at short wave lengths, especially at night, apparently due to the effective absence of ether absorption, then it becomes possible to "get thru" over relatively long distances with powers diminutive as compared with those required for giving a regular service. With these exceptional transmission conditions we are, of course, familiar. They are exemplified by the long distances reached at night by the amateurs, as across the Atlantic, and by the hearing of the normally 30-mile (48 km.) Catalina Island system in Australian waters. The transmission curves of Figure 3 account for these unusual long distance transmissions if we assume that the attenuation due to absorption is eliminated on these occasions by some natural cause. Thus, at 3,000 miles (4,800 km.) the curves for 1,000 kilocycles (300 meters), for example, show that were the absorption eliminated, the transmission equivalent would be improved by the difference between about 10.8 and 5.2 for $log_{10}\frac{I_1}{I_2}$ or 5.6, an improvement equivalent to a little over 100 miles of standard cable. The remaining or purely spreading-out loss of about 5 units, or 100 miles of standard cable, is then taken care of by the sending and receiving amplification.

Interference may occur in either or both of two ways—by the interference level rising to a point comparable with the normal transmission level at the receiving end of the ether circuit, or by the transmission level of the waves themselves dropping so low, due to excessive atmospheric absorption, as to fall below that of the atmospheric disturbances. For reliable transmission it is necessary, therefore, to deliver normally at the receiving end, a wave intensity sufficient to allow for the fluctuations which occur in atmospheric absorption and in the intensity level of the atmospherics. The importance of working to transmission level standards which give an adequate operating margin against interference, for the types of service required, will be appreciated from the foregoing. The following values of minimum transmission levels will be of value to know:

(a) For carrier wire telephone transmission at frequencies in the tens of thousands of cycles, the limiting interference may be our old friend "static," or interference from high frequency transients in power systems. Unless the lines are especially well transposed for these frequencies, the interference requires that

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the transmission level be kept above a minimum value of the order of $log_{10}\frac{I_1}{I_2}=1.2$ (about 25 miles of standard cable below zero level).

(b) While for radio telephone transmission the available data are as yet very meagre, we have obtained a few order-of-magnitude figures which should be of interest. For the Catalina Island radiophone system, for example, the minimum field intensity is estimated at roughly 1,000 microvolts per meter. The circuit is sometimes quite noisy during the summer months, altho not prohibitively so. In our ship to-shore radio telephone experiments along the Atlantic coast, we have on occasions worked with lower field intensities, as low as 100 microvolts per meter. The latter figure, however, gives a grade of service far below wire standards.

(c) The best data on the minimum permissible transmission level for radio telegraphy are those obtained from the experience in trans-Atlantic telegraph operation. The figures prevailing for present trans-oceanic radio-telegraph operation are understood to lie in the order of 10 to 100 microvolts per meter, depending upon individual cases and the time of the year.

The Net Transmission Equivalent

The net over-all transmission equivalent of the system is measured by the ratio of the transmitted to the received signaling power, and is shown in Figure 4 as the difference between the transmission levels at the two ends. This relatively small loss represents the difference between two large values, the transmission loss and the transmission gain thruout the system. Relatively small changes in either the attenuation or amplification may, therefore, cause large changes in the net equivalent of the circuit, thus tending to give rise to instability in the transmission performance of the circuit.

This problem of fluctuation becomes very serious with the use of very high frequencies, whether transmitted by wires or by radio. Were we to attempt to employ, for example, a million cycles for wire carrier transmission over considerable distances, as has been proposed, not only would the losses be very large, but they would be unstable, changing with weather conditions, so that the maintenance of a constant volume of transmission, would become extremely difficult. Similarly in radio transmission the fluctuations in the ether attenuation, particularly at short wave lengths where over long distances we experience

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the well-known "swinging" or fading effects, render the maintenance of a satisfactory volume of transmission a difficult problem. As noted, above these fluctuations, particularly as between day and night transmission with very high frequencies, may be enormous.

It is of value to the radio engineer to have some idea of the over-all circuit transmission equivalents which are necessary for satisfactory telephone communication. In the wire telephone art, the maximum equivalent between subscribers is ordinarily taken as about 30 miles of standard cable, or $log_1{}^0 \frac{I_1}{I_2} = 1.4$. Under quiet conditions, considerably larger transmission equivalents can be talked over. The long distance toll lines themselves are usually designed for transmission equivalents of 0.5 to 0.75 or 10 to 15 miles of standard cable. These figures will serve as a general guide for the transmission equivalents which radio telephone circuits should provide. Where a radio circuit forms a link in a direct wire circuit as, for example, in the case of Catalina Island, it is desirable to work the radio link as close to a zero equivalent as possible, that is, to give out at the receiving end a volume nearly equal to that fed in at the transmitting end.

Two-Way Operation

When the two one-way radio channels are merged at their two ends into a regular telephone circuit for connection to the wire network, as illustrated in Figure 5, then there is a limit in the transmission equivalent which can be given over the radio part of the circuit.

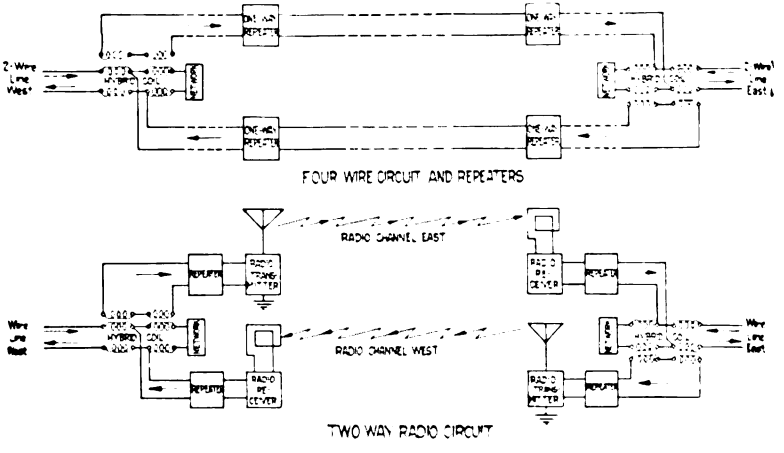

FIGURE 5

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This limit will be appreciated by reference to Figure 5. It is imposed by the tendency of the two one-way channels to form a round-trip circuit by "feeding-back" from one to the other via the voice frequency connecting circuit. If the total amplification around the circuit, including the voice-frequency line, exceeds the total losses in the circuit, "singing" will result. Were no line balance provided at the voice frequency terminals, then it would be impossible to operate the circuit at a zero equivalent. By setting up a balancing circuit at each end in the manner illustrated, a transmission loss is, in effect, inserted between the sending and receiving sides of the voice circuit, which tends to prevent this sing-around action. Actually, there is a limitation in the degree of balance which can be realized between the telephone line and the balancing network, especially if the telephone line is to be switched at a nearby central office, and this factor, together with the margin of safety which is required between the operating condition and the singing condition, prevents the radio channels from being operated much better than the zero equivalent. This whole matter of realizing in practice an adequate transmission equivalent, will be appreciated to be an especially difficult problem in the case of marine radio telephony, where the connection is switched from one vessel to another at varying distances.

It should be noted further, with reference to two-way operation, that the difficulty of effecting simultaneous sending and receiving at a station arises primarily from the large attenuation which must be overcome and the resulting large ratio between the energies transmitted into and received from the ether. The receiver must be prevented from being overloaded by the home transmitter and this, in general, requires that there be provided between the high frequency side of the transmitter and that of the receiver, a transmission loss comparable in size to that obtaining over the radio circuit itself. This "separating" transmission loss is ordinarily provided (a) by frequency-selecting circuits (tuned circuits and filters), the sending and receiving transmissions being placed on different frequencies, (b) by balance, as when using the blind spot of a loop-antenna receiver, and (c) by spatial separation between sending and receiving points, where the large step-off loss is used to advantage.

Transmission Levels on Combination Wire and Radio Telephone Systems

It will be of interest to trace thru the approximate transmis-

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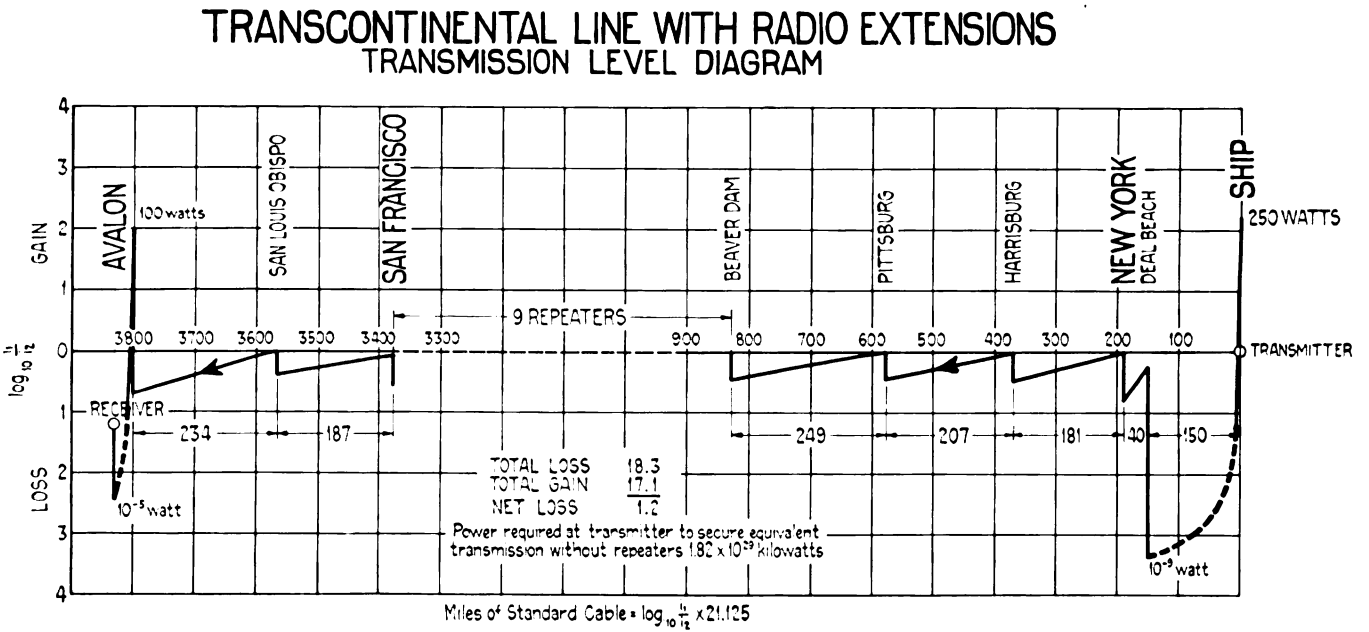

FIG RE 6

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sion levels which obtain for a radio system linked up with a long repeatered land line system.

In Figure 6, there is taken a rather striking example of this case in the trans-continental telephone line as connected up to radio extensions at its termini—to Catalina Island on the Pacific and to a vessel at sea on the Atlantic. The tranmission illustrated is that occurring from east to west. The voice currents start out from the vessel at zero level, are amplified to a relatively high level and upon being transmitted to the shore 150 miles (240 km.) away, drop to a very low level. At the shore radio station they are boosted up, at New York amplified again, and put upon the trans-continental circuit. Regularly at about 300 miles (480 km.) the telephone repeaters pull back the transmission level to about its original value. In the radio link at the western end the currents are again amplified to a high level at the transmitting station, drop down to a very low level at the receiver and are brought back to a level at which they can be heard. Actually in the receiving telephone the transmission is about $log_{10} \frac{I_1}{I_2} = 1.2$ below zero level, or roughly 25 miles of standard cable "down." The total loss and the total gain in the circuit is enormous, as is shown by the figures given in the diagram. This is a rather striking illustration of the extent to which amplification properly distributed and maintained can be used to overcome attenuations enormous in the aggregate. Just to give a better idea of what these values of attenuation and amplification mean, I would note that were it necessary to supply at the transmitting end all of the amplification required for delivering this volume of transmission to the receiving end thru the combination circuit, the kilowatts required would be measured by a twenty-nine place figure, an amount of power unavailable in the world. The importance of correctly distributing the amplification along the system is well illustrated by this figure by comparing it with the signaling power actually represented in the system, which sums up to something less than 1 kilowatt. The difference is simply a question of the transmission level at which the amplification is worked.

Figure 7 gives a view of the interior of one of these radio telephone stations—that of the American Telephone and Telegraph Company and Western Electric Company—located at Deal Beach, New Jersey. In the foreground is the switchboard for enabling the operator to control the radio-wire circuit at the connecting point. In the background are the transmitter units—

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four of them. These, together with the four antennas with which the station is equipped, "multiplex" the ether, in effect, and permit four channels to be established to as many distant stations. It is intended that three of these be telephone talking channels and the fourth a signaling or a reserve talking channel. The

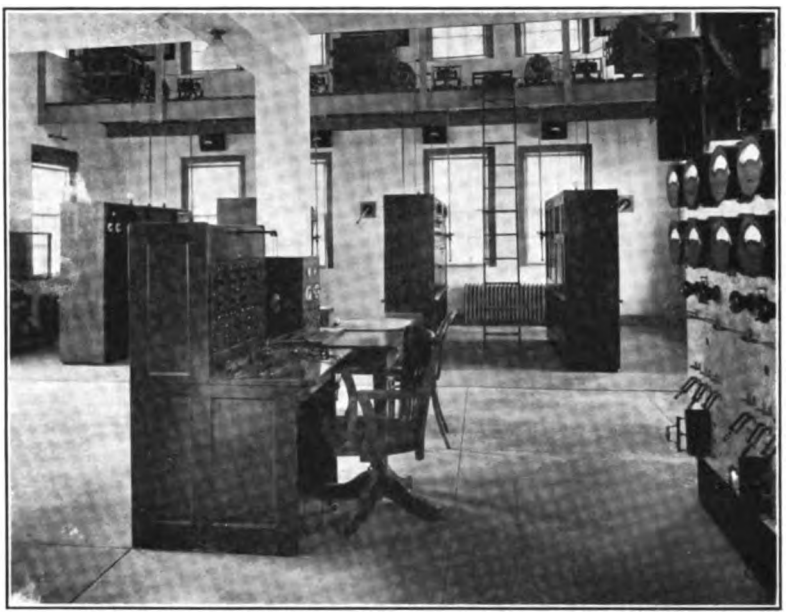

FIGURE 7

receiving station is located at another point. It is not desired to describe this station in any detail, but merely to illustrate it as an example of a radio repeating station functioning to connect the wire system with ships at sea and capable of effecting simultaneously three different connections. It is hoped that this ship-to-shore development may be itself the subject of an INSTITUTE paper.

INTERMEDIATE REPEATERS

The trans-continental line with radio extensions as shown in Figure 6 is a good illustration of the use of intermediate repeaters generally. Two types of repeaters are represented, the straight wire telephone repeaters and the shore radio stations which are in effect huge repeaters relaying between the land line and the radio circuits.

Because of the moderate attenuation obtaining in the wire transmission system, we can work with fairly long repeater

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spacing, about 300 miles in this case, and with moderate amounts of power and yet keep the transmission levels at the receiving end relatively much higher than is usual in radio systems. Due to the large attenuations obtaining over the radio extensions,

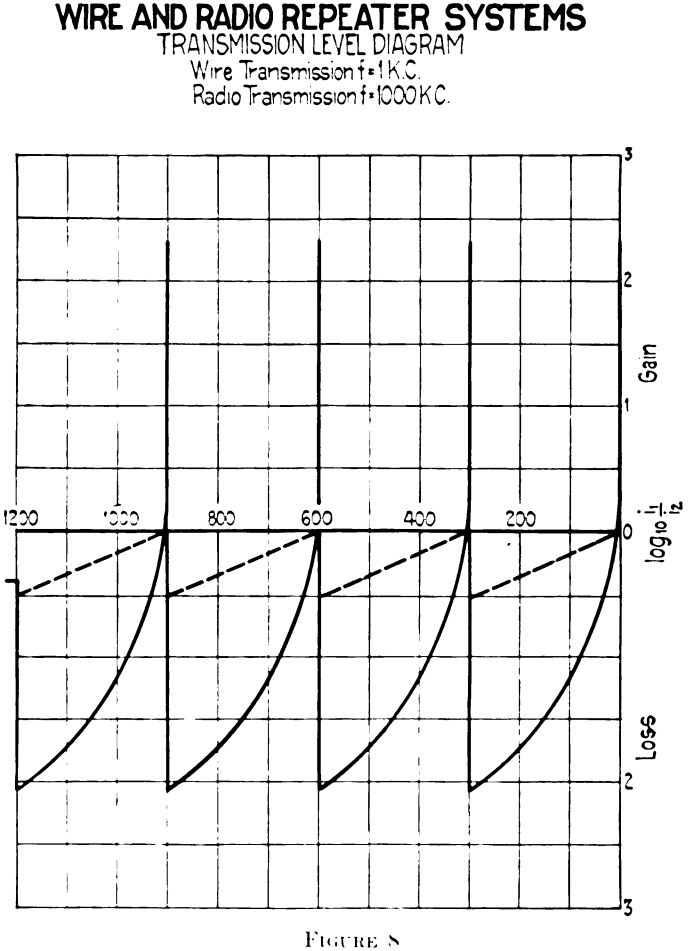

FIGURE 8

the radio repeaters must put out a high transmission level, making them costly, and even with this relatively high output, the level drops to very low values at the receiving end. This falling off occurs largely in the get-away loss at the transmitting end of the radio circuit, as the diagram indicates.

Figure 8 depicts an all-radio system provided with intermediate repeaters and compares for illustration purposes the

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transmission levels obtaining therein with those for a wire system. The solid lines are for radio and the dash for wire. It will be seen that the radio system courses thru wide transmission level variations as compared to the ordinary wire system, due to the large attenuations obtaining and particularly to the large step-off loss near the sending station

The figure illustrates the same spacing for both radio and wire repeating and gives a measure of the difference in amplification required in the two cases. Altho in the radio repeaters the level can be permitted to drop to low values, nevertheless a large part of the total amplification has to be supplied at relatively high power levels, and it is this fact, together with the antenna structures required at each point to "get into" the ether transmission medium anew, that militates against the economics of radio repeaters as compared with straight-away radio transmission. The tendency will be to "stretch out" the straight-away transmission due to the fact that for the longer distances the transmission loss increases relatively slowly. While we may look for some important uses of radio repeaters in special cases, we should not, in general, expect them to be as important to the radio art as are wire repeaters in wire operation.

Transmission of Side Band Without Carrier

In dealing with the subject of power levels in radio transmission, it is important to recognize that a modulated radio telephone wave consists of two components, one, the carrier frequency itself and the other, the so-called side bands, which are the actual modulated components. This resolution of the modulated carrier into two or, rather, three components, the carrier and two side bands, has been given mathematically a number of times and need not be repeated. It is physically analogous to the resolution of the uni-directional current of a microphone transmitter into direct current and alternating current components, the direct current corresponding to the carrier and the alternating current to the modulated components.

Now, the important thing about this matter of side bands and the unmodulated carrier component, with reference to transmission considerations, is this:—that it is the side bands alone, and not the carrier, which convey the actual intelligence. The function of the carrier comes in merely at the receiving end, in the detector, as a means for translating the side band from radio frequency back to audio frequency.

This will be made clearer by reference to Figure 9. At the

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bottom of the figure is shown schematically a one-way radio system. Above it is depicted the voice-frequency band, showing the manner in which it is shifted by modulation up to the carrier frequency range, and at the receiving end, by detection, back to the voice-frequency range. The voice-frequency band, as it comes out of the ordinary telephone transmitter, is shown at

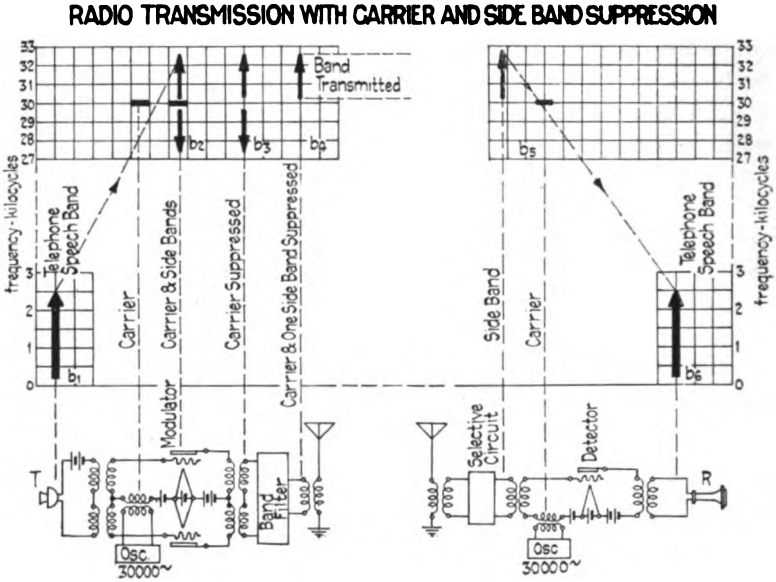

FIGURE 9

(b_1) at its normal telephone-frequency position. Upon modulation with the carrier the reference point of the voice-frequency band is shifted from zero frequency (direct current) up to the carrier frequency as shown at b_2 where the two side bands appear. The effect of modulation is, therefore, simply to shift the band of signaling frequencies upward in the frequency range and refer it in a double relation to the carrier frequency.

Located between the upper and lower side bands in the figure, there is indicated the unmodulated component of the carrier. The fact that this component is unnecessary so far as the actual intelligence-carrying energy is concerned, is proven by the fact that it need not be transmitted to the receiver. The carrier may be suppressed as shown at b_3. A means for doing this is the Carson balanced tube modulator circuit illustrated below in the figure.

A reduction of the total band can be effected by filtering out

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one of them as shown at b_4. The remaining single band is the simplest component of the modulation process with which intelligence can be transmitted to the distant end. Upon arriving at the receiving end at b_5, this side band is fed into the detector along with a carrier of the same frequency as that employed at the sending end; these two components demodulate one another, with the result that the side band is shifted down to its original audio-frequency position in the scale, as indicated at b_6.

Actually this general method of transmission, involving both carrier suppression and side band elimination, is being employed in wire carrier systems in the Bell Telephone Plant.[5] I am briefly explaining it here because it represents a valuable improvement in wire transmission which should have important applications in radio.

From the standpoint of transmission levels its application is in showing that the real intelligence-carrying component of a radio wave is the side band and not the carrier itself. In considering transmission levels accurately care should be taken, therefore, to deal in terms of the level or wave-intensity of the side band component and not the carrier. It is because of this that as nearly complete modulation as possible is desired at the transmitting station.

It follows that the power resident in the carrier is a pure waste in so far as overcoming interference is concerned. An important power saving can be effected in the transmitting station by providing some such means as is illustrated whereby the carrier power is held back in the circuit. The two side bands together can never be greater in current and voltage value than the carrier, and each side band alone cannot be greater than half the carrier. The power of the carrier is therefore always at least four times the power of one side band or twice that of both together. Thus by "holding-back" the carrier at the transmitter we can transmit with but one-third the power ordinarily required. Actually the power saving is much greater than this because of the necessity of normally working with larger ratios between carrier and side band in order to accommodate the peaks of the telephone waves and thereby preserve the quality of transmission. The power saving is, of course, especially important in long distance work.

[5] "Carrier Current Telephony and Telegraphy," by Colpitts and Blackwell, "Journal of the American Institute of Electrical Engineers," February 16-18, 1921.

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The suppression of one of the two side bands halves the frequency band required for transmission and would double the message-carrying capacity of the ether were no frequency range required to space the channels apart. This advantage of the present method is likewise of special importance in long-distance-long-wave transmission.

Quality of Transmission

We have spoken above of factors concerned with the volume of transmission and only incidentally of that other requisite of transmission, namely, good quality. Without going into this matter in much detail, it will be well to make note of the several factors involved in obtaining good quality, as follows:

1. It is important that a substantial *band* of voice frequencies be transmitted. Of course distorted talk can be transmitted on a relatively narrow band, but commercial transmission has been found to require a single side band width of the order of 2,000 or more cycles, the band width increasing with the quality desired, up to about 5,000 cycles.

2. It is necessary that the distortion which is due to non-linearity of transmission with respect to amplitude, be avoided. This is equivalent to saying that there should not be permitted to take place self-modulation between the components of the side band, nor the too close cutting-off of the peaks of the telephone waves due to saturation effects.

3. The transmission must be kept free from interfering noises. The ratio between interfering noise current and voice currents of the order of 0.1 is regarded as large in wire practice. While this amount of interfering current will not prohibit service, it does seriously impair the effectiveness of transmission and annoys the listener. In radio the ratio of static noise to signal strength is very often much greater than this value. As the radio art progresses, it will be necessary to work toward standards more nearly in keeping with those which have been found necessary for wire service.

The writer wishes to express his indebtedness to the following of his associates for helpful suggestions and assistance: Messrs. J. R. Carson, Ralph Bown, and D. K. Martin.

SUMMARY: The transmission losses in wire and radio communication are compared for various frequencies and distances of transmission. The effect of natural and signal interference at the receiving ends of such systems is described, and conclusions drawn as to the necessary minimum transmission levels to be maintained in wire and radio circuits. The limitations on two-way operation resulting from "singing" of the entire system are considered in each case,

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and for combination wire and radio circuits as well. The comparative usefulness of repeater stations for wire and radio used is derived. Several means of effective wire and radio telephony are described, notably transmission on one side band only. The transmission requirements in numerical form of a radio telephone system are then given.

APPENDIX:—The curves of Figures 2 and 3 are based upon the following equations and data:

The radio curves are based on the familiar Austin-Cohen formula:

$$I = \frac{7.8\times10^{-10}\, h_r\, h_s\, f\, I_s}{Rd}\, \varepsilon^{-4.4\times10^{-6} d\sqrt{f}} \qquad (1)$$

where I = amperes
R = ohms
h = meters
f = cycles
d = miles

Taking equal antenna heights at two ends $h_s = h_r$.

As regards antenna resistance we assume symmetry as between the two ends, and that the external (radiation) resistance of the antenna equals the resistance within the antenna (which resistance would be internal apparatus resistance in the case of a perfect antenna). This makes R_r radiation resistance $= R_i$ ohmic resistance; and R of (1) becomes $= R_r + R_i$

$$\text{where } R_r = 17.8\times10^{-15} h^2 f^2 \qquad (2)$$

Expressing in terms of current ratio and substituting values of R, (1) becomes,

$$\frac{I_s}{I_r} = 45.5\times10^{-6} f d\, \varepsilon^{4.4\times10^{-6} d\sqrt{f}} \qquad (3)$$

In order to plot this equation on the same basis as we usually plot wire attenuation, the logarithm of the ratio is used, thus:

$$\log_{10}\frac{I_s}{I_r} = \log_{10} 45.5\times10^{-6} f d + \frac{4.4\times10^{-6}}{2.303} d\sqrt{f} \qquad (4)$$

which is the equation of the curves plotted.

The ratio of the currents in the two antennas is in this case a true measure of the transmission because they are in circuits of equal impedances, by the assumption of antenna symmetry.

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Data for the Wire Curves

$$a = \frac{R}{2}\sqrt{\frac{C}{L}} + \frac{G}{2}\sqrt{\frac{L}{C}}$$

For number 8 Birmingham wire gauge open wire; dry weather. the constants per mile are:

diameter = 165 mils = 4.19 mm.

wire spacing = 12 inches = 30.5 cm.

40 poles per mile.

$$L = 3{,}370\ \mu\text{ h.}$$

$$C = 9{,}140\ \mu\mu\text{f.}$$

Frequency, Kilocycles

	1.	20.	100.	1,000 units
$R =$	4.14	10.0	21.5	65.7 ohms per loop mile
$G =$	0.55	10.0	*50.0	*500.0 μ mhos per loop mile
$a =$	0.003488	0.0112	0.03289	0.2059

*Estimated

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DISCUSSION*

John R. Carson (by letter): Mr. Espenschied in his interesting paper has performed a distinct and important service to the radio profession in translating into the terms of radio transmission the engineering principles which have been so successfully applied to telephonic transmission and which, indeed have raised the latter art to the level of a science. It is my belief, however, that there are certain limitations inherent in radio transmission which prevent a complete correlation of the engineering principles governing the two arts. A failure clearly to understand this fact may lead to incorrect deductions from the paper under discussion.

In this connection I particularly wish to discuss briefly the bases of comparison of the formulas and curves (Figures 2 and 3) of wire and radio transmission. This comparison is, I believe, very likely to be misinterpreted in a way unduly favorable to radio unless the underlying assumptions are clearly understood and their limitations recognized.

In wire transmission it is almost universal practice to fit the terminal impedances to the line; that is, to make the terminal impedances, as seen from the line, equal to the line impedance. As is well known, this condition eliminates reflection at the terminals and assures maximum energy transmission. In comparing wire and radio transmission Mr. Espenschied has assumed a corresponding condition for the case of radio—namely, that the *ohmic* or *dissipative resistance* of the antenna (which includes the equivalent load or terminal resistance in series with the antenna) is equal to the *radiation resistance.* This is the theoretical condition for maximum energy transfer and might seem like a fair and reasonable basis for comparison. The point I wish to emphasize, however, is, that in the case of radio transmission, this condition is only realizable over a relatively narrow range of frequencies, and that deductions drawn regarding variation of efficiency with frequency are quite deceptive except within narrow limits.

The reason, in brief, why the conditions assumed in wire transmission lead to deceptive and even impossible conclusions when applied to radio transmission, is the relatively low value of the radiation resistance of an antenna even at very high frequencies, and its rapid decrease with decreasing frequencies. For example, consider an antenna with an effective height of

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100 meters; its radiation resistance for representative frequencies is given in the following table:

f	Radiation Resistance
10^6	178 ohms
10^5	1.78 ohms
10^4	0.0178 ohms
10^3	0.000178 ohms

Now the conditions assumed are that the dissipative resistance of the antenna itself plus the equivalent resistance of the generator (or receiver) in series with the antenna is equal to the radiation resistance. Inspection of the table above shows that this condition is not realizable at frequencies less than 100 kilocycles. On the other hand, at frequencies above 1,000 kilocycles (10^6 cycles/second), the antenna height begins to approach the wave length and the radiation resistance ceases to increase in accordance with the square law. Furthermore, at high frequencies, the equivalent dissipative resistance of the antenna becomes quite large and increases rapidly with the frequency.

A brief analysis of the transmission formulas will serve to emphasize the foregoing considerations. The current in the transmitting or sending antenna is

$$I_s = \frac{E}{R_\omega + R_r}$$

where E is the equivalent emf. of the generator in series with the antenna; R_ω is the dissipative resistance of the antenna, including the equivalent resistance of the generator in series therewith; and R_r is the radiation resistance which may be taken as $k\,(h\omega)^2$, k being a numerical factor depending on the units employed. The energy radiated is

$$W_r = \frac{E^2 R_r}{(R_r + R_\omega)^2}$$

the total energy developed is

$$W_T = \frac{E^2}{R_r + R_\omega}$$

and the transmitting efficiency is

$$\eta = \frac{R_r}{R_r + R_\omega}$$

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Now the condition for maximum radiated energy is clearly $R_\omega = R_r$; introducing this condition we have:

$$W_r = \frac{E^2}{4R_r} = \frac{E^2}{4k(\omega h)^2}$$

$$W_T = \frac{E^2}{2R_r} = \frac{E^2}{2k(\omega h)^2}$$

$$\eta = 1/2$$

We are thus led to the conclusion that for a given generator, *the maximum energy radiated is inversely proportional to the square of the frequency and the square of the antenna height.*

Now in accordance with this condition let us suppose that we make the product (ωh) smaller and smaller, ultimately the radiation resistance would become so small that the condition $R_\omega = R_r$ can no longer be maintained and we should actually get

$$W_r = \frac{E^2 R_r}{R_\omega^2} = \frac{E^2 k(\omega h)^2}{R_\omega^2}$$

$$W_T = \frac{E^2}{(R_r + R_\omega)} = \frac{E^2}{R_\omega}$$

$$\eta = \frac{k(\omega h)^2}{R_\omega}$$

That is, we should actually find that the factor $(\omega h)^2$ appears in an entirely different way than it does in the ideal case where $R_\omega = R_r$.

The same considerations apply to the phenomena of reception. Consider an antenna of height h, dissipative and radiation resistances R_ω and R_r, in a radiation field in which the electric intensity parallel to the antenna is E. Assuming perfect tuning, the current I_k in the antenna is

$$I_k = \frac{Eh}{R_\omega + R_r}$$

and the energy absorbed is

$$I_k^2 R_\omega = \frac{R_\omega E^2 h^2}{(R_\omega + R_r)^2}$$

This is a maximum when $R_\omega = R_r$, in which case

$$I_k^2 R_\omega = \frac{E^2 h^2}{4 R_\omega} = \frac{E^2}{4k} \frac{1}{\omega^2}$$

In other words, the maximum energy absorbable by the antenna is independent of the height and inversely proportional to the frequency

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Here again the conclusions are quite deceptive when pushed to the limit. For if the frequency is reduced sufficiently, R_r becomes relatively negligible and ultimately

$$I_k^2 R_\omega = \frac{E^2 h^2}{R_\omega}$$

This formula shows that the energy absorbed under these conditions is proportional to the square of the antenna height but independent of the frequency.

In a similar manner the formula given in Mr. Espenschied's paper for the ratio of the sending and receiving currents is based on assumptions which are realizable only within narrow limits.

I do not wish to be misunderstood as failing to recognize the practical usefulness of the curves and formulas under discussion. As Mr. Espenschied says, they can be used for obtaining the loss in any practical case simply by taking the minimum (or theoretical loss) as given by the curves and adding thereto the additional loss obtaining in the actual antenna. I do wish, however, to emphasize the danger of drawing incorrect inferences regarding variation of efficiency with respect to frequency and height of antenna from the curves alone.

June 14, 1922.

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A METHOD FOR TESTING AND RATING ELECTRON TUBE GENERATORS*

By

L. M. Hull

(Associate Physicist, Bureau of Standards, Washington, D. C.)

When used as a generator of alternating currents, an electron tube is associated with a mono-periodic electrical system and with a source of direct-current power. These are fundamental. Departures from this ideal state due to extraneous capacities, distributed circuit constants, and the like, are frequently encountered in practice. But like most ostensibly basic theory, the calculations employed in the present discussion will treat only the predominant effects.

Over two years ago a scheme was outlined by the writer for calculating approximately the power output from a given triode, in terms of the constants of a highly periodic output circuit, and of the "oscillation characteristic" of the valve, as determined by static method.[1] It was assumed at the outset that in the steady-state oscillation process the alternating plate and grid voltages are sinusoidal, opposite in phase, and maintained in a constant ratio of amplitudes, for a given coupling ratio. Graphical analysis of a given oscillation characteristic taken on this basis, tho tedious, yields results which are in striking quantitative agreement with experimental data obtained on oscillating systems, provided that certain circuital conditions are complied with, which are not seriously restrictive when dealing with radio-frequency circuits.

The brief theory in the paper referred to above was descriptive, rather than mathematically elegant. Similar conceptions of tube operation have since been presented in more complete mathematical form by Appleton and van der Pol[2] and others.

* Received by the Editor, June 6, 1922.

[1] "Determination of the Output Characteristics of Electron Tube Generators." Scientific Paper of the Bureau of Standards, Number 355, December 1, 1919.

[2] Appleton and van der Pol, "Phil. Mag.," 42, 201-220, August, 1921. See also van der Pol, "Radio Review," 1, 701-710, and 754-762, November and December, 1920.

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For practical applications the existing theory is not satisfactory or final. In a triode generator the primary phenomena are almost invariably complicated by secondary and thermal emission from grid and plate, non-uniform filament temperature, and other irregularities. As a consequence of the impossibility of obtaining even an approximate solution of the current-flow problem within the triode, the only useful volt-ampere valve characteristics are those experimentally determined. Computations from these characteristics are necessarily graphical. It is quite impossible, moreover, to obtain the data for even static volt-ampere characteristics with most commercial valves, on account of the excessive heating of the electrodes. For these reasons it seems desirable that certain coefficients of electron tube generators be defined, which serve to determine their behavior in radio-frequency circuits; also that methods of measurement of these coefficients for any triode be devised, these methods being analogous to those employed in measuring the coefficients of amplification and detection. An audio-frequency bridge arrangement is being used by the writer for this purpose, with a degree of success which seems to merit a detailed description.

Preliminary to a discussion of practical results, we shall consider briefly the basic theory of the conversion of direct-current power into alternating-current power by an electron tube.

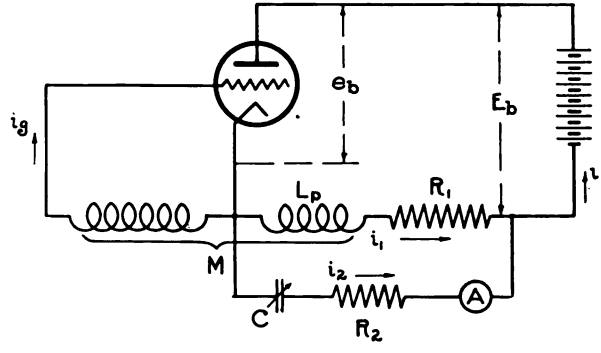

FIGURE 1—Semi-Direct-Coupled Generating Circuit

Take as a typical case the familiar semi-direct-coupled circuit shown in Figure 1. Forgetting for the moment just how and why the instantaneous volt-ampere relation happens to be as it

E. Takagishi, "Electrician," 86, 346-348 and 374-375, March 25 and April 1, 1921; "Sci. Abs.," B, Number 642, June, 1921.

E. V. Appleton, "Radio Review," 2, 419-424, August, 1921.

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is, for the triode, it appears that the fundamental features of this system are as follows: a parallel periodic circuit connected in series with a source of direct-current power of voltage E_b and with a variable resistance, T, of such a nature that its volt-ampere characteristic has a slope which is negative for at least a portion of the operative range. The symbols refer to Figure 2.

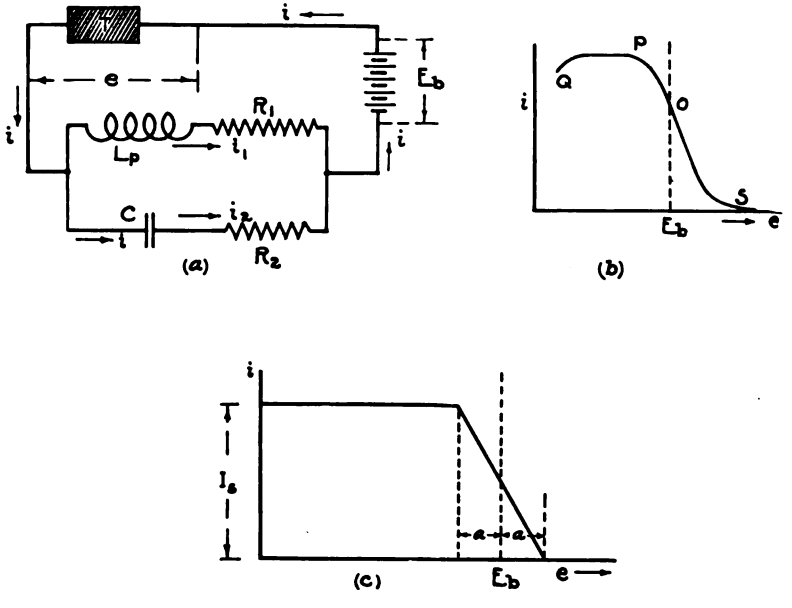

FIGURE 2

A solution for the vibrations of such a system has been the purpose of much diligent investigation since Barkhausen's first work on the theory of the singing arc. Dr. van der Pol[3] develops the function $i=f(e)$ as a power series about the point $e=E_b$, and obtains an approximate solution by a method similar to that suggested by Lord Rayleigh ("Theory of Sound") for small vibrations under a variable restoring force. It seems probable, however, that such a method tends, by the nature of its approximations, to conceal factors which are most conspicuous in fixing the stable amplitudes. In determining power output, the region PQ is usually more significant than the region PS of the characteristic. The terms in a series expansion about the point O which describe the shape of the characteristic at the point Q are just those terms which must be lopped off to fit into the

[3] "Radio Review," previous citation.

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differential equation, if the latter is to be manageable. It is possible, however, by a slightly roundabout process, to arrive at an approximate solution which checks with a goodly variety of experimental results.

This procedure is based upon the assumption of small dissipative resistance in the output circuit, compared with the reactance of either branch, and upon the fact that the fundamental angular frequency of the steady-state oscillation is approximately $\frac{1}{\sqrt{LC}}$. Altho the frequency at which this steady oscillation occurs cannot be deduced precisely by mathematical analysis, it is not difficult, by theoretical reasoning, to set sufficiently narrow limits upon the range of frequencies over which this oscillation can occur. Suppose the function $i = f(e)$ is specified, empirically or otherwise. A possible form for $f(e)$ is that shown in Figure 2 (b). This oscillation characteristic can be represented to any desired degree of accuracy by a discontinuous curve composed of rectilinear segments. The simplest approximation to it is the symmetrical curve of three segments shown in Figure 2 (c). Then at any instant of time when the total voltage e across the impedance T lies between the limits:

$$-a < e < +a$$

or when

$$e < -a$$

$$e > +a$$

the motion of the system can be described by a linear differential equation with constant coefficients. The voltage e can be expressed as a function of time, in terms of the circuit constants and of the constant slope of the characteristic, for periods or epochs of time during which it is passing over any one of the rectilinear segments of the characteristic. Each of the alegebraic equations so obtained contains two unknown constants. The values of e at the end points of the segments are known, however, and the problem is narrowed down to a determination of the *time derivative* of e at one end point of each segment. By making use of the criterion for steady oscillation, namely, that at some convenient end point, say $e = +a$, the time derivative of e shall always be the same, each time the oscillation reaches this particular displacement, we obtain n transcendental equations in n unknowns, n being the total number of segments of the characteristic. The unknowns are the end-point values of the time derivative of e.

In the case of three segments, disposed about the operating point as shown in Figure 2, the solution of these steady-state

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equations can be readily obtained. The process of solution, while tedious, is perfectly straightforward and involves nothing but algebraic manipulations. The resulting equation for the fundamental frequency of oscillation exhibits the following interesting fact: The steady-state oscillation which takes place on characteristic composed of three rectilinear segments of the type shown in Figure 2 (c) cannot have a fundamental frequency which exceeds the transient frequency of the circuit isolated from T, or which is less than the transient frequency of the circuit when it is shunted by a constant resistance equal to the absolute value of the minimum resistance assumed by the variable impedance in the region $-a$ to $+a$.

Of course the curve of Figure 2 is not a practical oscillation characteristic. When carried thru in detail, however, the analysis sketched in the foregoing paragraphs shows that any alteration in the slope of a section of the characteristic which is small compared with the region a a will influence the stable frequency to an extent which is small, even in comparison with the difference between the limiting values of frequency specified above. Thus while it may be impossible to calculate exactly the stable frequency in the case of a continuously curved characteristic, we can, at least, always determine the degree of approximation involved in assuming that this frequency is $\frac{1}{\sqrt{LC}}$, by measuring the slope of the oscillation characteristic at the point where this slope is greatest. If the value of $\frac{\partial i}{\partial e}$ at this point is h, then it is known that the stable frequency, ω_f can not be less than

$$\omega_1 = \sqrt{\frac{1}{LC} - \frac{1}{4}\left(\frac{R}{L} + \frac{h}{C}\right)^2} \tag{1}$$

nor greater than

$$\omega_2 = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \tag{2}$$

In these equations R is the total dissipative resistance of the output circuit.

In most cases, to a high degree of accuracy, $\omega_2^2 = \frac{1}{LC}$; that is, the difference between ω_2^2 and $\frac{1}{LC}$ cannot be detected experimentally, whereas the difference between ω_1 and ω_2 is sometimes measurable. The writer has measured the mean slope of the upright portion of the oscillation characteristic of a number of

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tungsten-filament valves varying from 5 watts to 250 watts power capacity. These measurements were made on a number of oscillation characteristics for each valve, taken to correspond to various operating conditions in the radio-frequency circuits. All of these mean slopes lay in the comparatively narrow range of values: 10^{-4} to 3×10^{-3} inverse ohms. These values of h when substituted in equation (1) with values of L and C appropriate to sharply tuned radio-frequency circuits varying in natural wave length from 600 to 4,000 meters, gave values for the frequency which always lay between ω_1 and ω_2. The outstanding fact is, however, that with high-frequency output circuits having a free decrement per semi-period anywhere between 0.01 and 0.25, the computed difference between ω_f and ω_2 never exceeds one per cent., even with the highest values of h, and generally is of the order of one part in a thousand. This is contrary to common experience, where the quantities L and C are measured separately, and then determinations are made with a wave-meter of the fundamental frequency of oscillations maintained in the circuit by a subsequently attached triode. Absolute measurements of L and C can seldom be made with an accuracy greater than one per cent. Measurements of $(\omega_f-\omega_1)$ can, however, be made and repeated consistently with a total variation not exceeding five parts in ten thousand, by the use of an auxiliary driving circuit and a wave-meter with a sensitive current measuring instrument. The oscillatory circuit is connected to the triode in condition for use, except that the filament is not lighted. A thermo-galvanometer is loosely coupled to the output circuit and the auxiliary generator is tuned to resonance with this circuit. The wave-meter is tuned to resonance with this generator, the generator turned off, and the test triode allowed to maintain oscillations in the original circuit. The wave-meter is retuned to resonance with the fundamental of these oscillations, and the difference between the two wave-meter settings gives $(\omega_f-\omega_2)$. In this way the corrections due to electrode capacities, coil capacities, etc., are avoided, and surprisingly small values for $(\omega_f-\omega_2)$ are found. Measurements made in a given high-frequency circuit at wave lengths of from 1,500 to 4,000 meters, using consecutively two 5-watt triodes, a 50-watt tungsten-filament triode, and a 50-watt oxide-filament triode yielded absolute values for the quotient $\frac{\omega_f-\omega_2}{\omega_f}$, which under no conditions exceeded 0.6 per cent. It was greatest when using the oxide-filament tube, owing to the excessive filament emission.

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It is not worth while to relate in detail the results of these experiments, since the whole question is one of what might be termed second-order importance in determining the net power output. The outstanding fact is that with an output circuit in which the effect of resistance on the free oscillation frequency is negligible, the difference between the free oscillation and the fundamental of the forced oscillation is less than one per cent of the former, with most existing types of triodes. The use of a hard, high-voltage triode tends to decrease this difference; the use of a soft tube or of a high-current tube tends to increase it. These considerations do not apply to generating circuits in which the series resistance of any branch is comparable with the reactance of that branch.

In what follows it will be assumed that the fundamental frequency of the forced oscillation is $\frac{1}{\sqrt{LC}}$. This neglects the correction due to electrode capacities, but, as was remarked at the beginning, the present simple theory concerns only monoperiodic systems.

Reverting to Figure 2, if we eliminate all reference to the volt-ampere characteristic of the impedance T, and express i_1 and i_2 in terms of i, we have:

$$\begin{aligned} \frac{d^2 i_1}{dt^2} + \frac{R}{L}\frac{di_1}{dt} + \frac{1}{LC} i_1 &= \frac{R_2}{L}\frac{di}{dt} + \frac{1}{LC} i \\ \frac{d^2 i_2}{dt^2} + \frac{R}{L}\frac{di_2}{dt} + \frac{1}{LC} i_2 &= \frac{d^2 i}{dt^2} + \frac{R_1}{L}\frac{di}{dt} \end{aligned} \tag{3}$$

Having established the fact that the quantity $\frac{1}{\sqrt{LC}}$ may be taken as the angular frequency of the fundamental forced oscillation, a method for approximating the fundamental power output at once appears.

Suppose that $e = E_b + E \sin \omega t$ (4)

Then from the characteristic, Figure 2 (c),

$$i = A_o(E) + A_1(E) \sin \omega t + \sum_{n=1}^{\infty} [A_n(E) \sin \omega n t + B_n(E) \cos \omega n t] \tag{5}$$

The coefficients are all functions of E, for a given characteristic. The fundamental is in phase with $E \sin \omega t$, that is, the coefficient $B_1(E) = 0$, because $\int_o^{2\pi} f(E \sin x) \sin x \, dx = 0$ for any form of the function f. If we substitute for i

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in equation (3) and solve separately the resulting equations for i_1 and i_2, we have expressions for the fundamentals and all the harmonics of i_1 and i_2 in terms of the functions $A_1(E)$, $A_n(E)$ and $B_n(E)$.

On restricting ourselves further to output circuits in which the current distribution is determined practically by the reactances, the theory is limited to low-resistance audio-frequency systems and to a fairly wide range of radio-frequency systems, but the resulting expressions for the output currents are simplified to:

Fundamental:

$$\begin{aligned} {}_1i_1 &= -\frac{A}{RC\omega}\cos\omega t \\ {}_1i_2 &= \frac{A_1\omega L}{R}\cos\omega t \end{aligned} \tag{6}$$

Harmonics:

$$\begin{aligned} {}_ni_1 &= \frac{\beta}{n}\sqrt{(A_n^2+B_n^2)(1+\xi^2)}\sin\left\{n\omega t+\tan^{-1}\left(\frac{B_n+\xi A_n}{A_n-\xi B_n}\right)\right\} \\ {}_ni_2 &= -\beta n\sqrt{(A_n^2+B_n^2)(1+\xi^2)}\sin\left\{n\omega t+\tan^{-1}\left(\frac{B_n-\gamma_1 A_n}{A_n+\gamma_1 B_n}\right)\right\} \end{aligned} \tag{7}$$

Here $$\beta=\frac{n}{1-n^2}$$

$$\xi=\omega C(nR_2-\beta R) \text{ and } \gamma_1=\omega C\left(\frac{R_1}{n}+\beta R\right)$$

It is assumed explicitly that $\frac{1}{n^2-1}$ is very large in comparison with $C\omega$, and that $(1-n^2)$ is very large in comparison with $R_2 RC^2\omega^2$.

From these values for ${}_ni_1$ and ${}_ni_2$ a trigonometric series in ωt is obtained for e, and then a new series for i is developed in terms of this series for e, in place of the single term, equation (4). In order to estimate the relative magnitude of the above quantities, assume that γ_1 is negligible compared with one.

If $$R_1=R_2=0.01\,L\omega, \text{ then } \gamma_1=0.01\left[\frac{1}{n}+2\beta\right]$$

Then $${}_ni_2=-\beta n\sqrt{A_n^2+B_n^2}\sin\left(n\omega t+\tan^{-1}\frac{B_n}{A_n}\right) \tag{8}$$

and the alternating part of e is:

$$e=\frac{L}{RC}A_1\sin\omega t+\sum-\beta\sqrt{\frac{L}{C}}(A_n^2+B_n^2)\sin\left\{n\omega t-\tan^{-1}\frac{A_n}{B_n}\right\} \tag{9}$$

as compared with the quantity $E\sin\omega t$ with which we started.

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It is pleasantly apparent from equation (9) that this process is very rapidly convergent. This fact is a direct result of the assumption that $\omega^2 = \frac{1}{LC}$ and R_1 and R_2 are small compared with $L\omega$. In fact, if the circuit be so arranged that $\sqrt{\frac{L}{C}}$ is small compared with its square, the process need be carried no further, provided only that none of the harmonic amplitudes $\sqrt{A_n^2(E)+B_n^2(E)}$ exceed $A_1(E)$ for any value of the argument E. There are no definite limits. The approximation grows better, for a given value of E, the smaller the resistance relative to $L\omega$ and the greater the rapidity with which the amplitudes of harmonics in i converge with increasing values of n. This latter depends upon the form of the volt-ampere characteristic. It is fairly apparent, without more detailed computation, that the difference is negligible between the coefficients of the i series, when $i = f(E \sin x)$ and the coefficients when $i = f(E \sin x + \sum a_n \sin nx)$ where no value of a_n exceeds one per cent of E and where the series of coefficients $\sum a_n$ converges. The physical reason for this is, of course, that the parallel impedance of a periodic circuit is high for its resonant frequency and relatively low for all harmonics of this resonant frequency. Thus the "voltage drop" across the output circuit is high for the fundamental of i and low for all the current harmonics, even tho they are as large as the fundamental in amplitude.

Having established the fact, which is familiar to most experimenters, that under certain restrictions on the ratio of resistance to reactance in the output circuit, the alternating voltage e, and consequently the currents i_1 and i_2, are approximately sinusoidal, we have the following simple relations concerning the useful or fundamental power output and input:

$$\text{Power generated} = \frac{A_1^2(E)\,L}{RC} \tag{10}$$

$$\text{Power generated} = i_1^2 R = i_2^2 R$$

$$\text{Power supplied} = E_b\, A_o(E) \tag{11}$$

The latter expression for the power drawn from the battery E_b is the only positive term resulting from the multiplication of $(E_b + E \sin \omega t)$ by the trigonometric series for i, equation (5). The coefficients of the alternating terms are all negative if the characteristic is "falling," as shown in Figure 2(b), and indicate power furnished by the impedance T.

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Having found the conditions existing during the steady state oscillation of a general system as set forth in Figure 2(b), these considerations can be applied with only slight modifications to the tube-driven system of Figure 1. As is well known, a starting transient, and hence an ultimate steady state is possible for a wide range of conditions of the volt-ampere characteristic of the triode, provided that the mutual inductance M is of the right sense to make the total derivative $\frac{d\,i}{d\,e_p}$ negative at the starting point. If the circuit and valve conditions permit a starting transient with inverse damping, a steady state will ultimately be reached. Then during the steady state the instantaneous relation between e_p, the plate voltage, and i, the plate current, must have a negative slope for part of the operating range, and be of the same nature, qualitatively, as the characteristic of Figure 2(c). With oscillations of this sort, the current i_1 has a phase angle of 90° lagging with respect to the alternating plate voltage, equations (6) and (9), and the alternating grid voltage is 90° behind this current. This results in a constantly maintained phase relation of 180° between the alternating plate voltage and alternating grid voltage, provided that the quadrature component of voltage due to the flow of grid current thru the coil L_g is negligible compared with the voltage induced in this coil. The amplitude of the alternating plate voltage is $L_p\,\omega\,i_1$ and of the alternating grid voltage, $M\,\omega\,i_1$, the latter being sinusoidal to the same degree that the plate voltage is sinusoidal. Hence, to a first approximation, the alternating component of plate voltage, in addition to being opposite in phase to the grid voltage, bears a constant ratio thereto, for a given value of M and L regardless of the values of R and C. This may be called the plate-grid ratio, and is thus dependent upon the circuit, and not upon the tube. This fact enables the determination of the oscillation characteristic for a given triode, as a function of the alternating plate voltage, or of the grid voltage. Such characteristics, taken by static methods, must necessarily be made separately for each value of the plate-grid ratio, corresponding to each value of the ratio $\frac{L}{M}$ to be used in oscillatory circuits.

The flow of current in the grid circuit abstracts useful power from the output circuit because the fundamental of grid current is in phase with the alternating grid voltage, in contrast with the fact that the fundamental of plate current opposes the

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alternating plate voltage. The grid power is thus a loss, and is important, in that it limits the alternating-current power which any triode will supply. Hence the oscillation characteristic of the grid current and that of the plate current are, in practical cases, of almost equal importance. In Figure 3(a) are shown the oscillation characteristics of a typical, tungsten-filament, 5-watt, hard triode, operating at 300 volts plate voltage; the

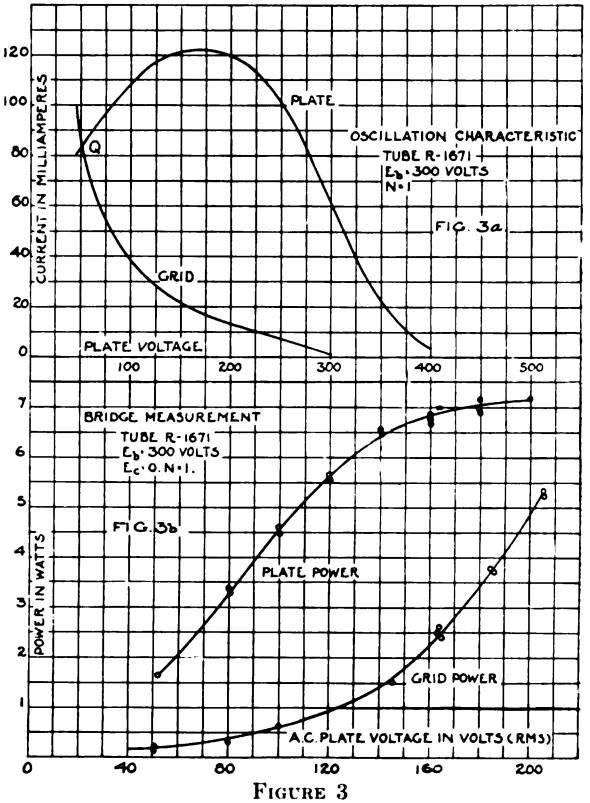

FIGURE 3

characteristic is shown for the value one of the plate-grid ratio, because that is the value which was used in subsequent measurements. The currents are plotted against the total plate voltage, e_p. The alternating plate voltage is merely $e_p - E_b$. These characteristics show how the grid current limits the useful power in two ways: first, by direct abstraction of power thru the grid coupling; second, by reducing the saturation current to the plate at the point Q, which increases the harmonics of plate current—chiefly the third—at the expense of the funda-

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mental. If it were not for the flow of grid current the fundamental of plate current would approach the constant value $\frac{2 I_s}{\pi}$ as the alternating voltages are increased, this value being the fundamental amplitude of a perfectly rectangular current wave, or $\frac{1}{\pi}\int_{\pi}^{2\pi} I_s \sin x \, dx$. This fundamental would remain constant until the alternating plate voltage approached the peak E_b, beyond which the fundamental of plate current would speedily disappear. Thus the maximum of power at the fundamental which can possibly be obtained from a triode having filament emission I_s operating at a steady plate voltage E_b, is $E_b \frac{I_s}{\pi}$.

Two quantities which are important factors or characteristics of a power tube are the fundamental grid resistance, R_g and the fundamental plate resistance, R_p. These may be defined as the quotients, respectively, of a sinusoidal impressed plate voltage by the fundamental plate current and a sinusoidal impressed grid voltage by the fundamental grid current; it is understood in the definition that these voltages are impressed simultaneously, bearing a definite ratio to each other, and being exactly opposite in phase. Thus for a given value of the plate-grid ratio, R_p and R_g are both functions of the amplitude of the alternating plate voltage. Suppose that R_p and R_g are known, empirically, as functions of E for a given value of $N = \frac{L_p}{M}$. Then for each value of E the average useful power output is:

$$P_o = \frac{E^2}{2}\left(\frac{1}{R_p} - \frac{1}{N^2 R_g}\right) \tag{12}$$

This equation, which involves only the triode characteristics, is related to the constants of an oscillatory output circuit thru the equation:

$$\frac{L}{RC} = \frac{E^2}{2P_o} \tag{13}$$

Thus if R_p and R_g are known graphically as a function of E, then substituting the same values of the parameter E in equation (13), we obtain an approximate relation between the power output and the parallel impedance, $\frac{L}{RC}$, of the output circuit, which should hold for any oscillatory circuit, in which the grid coupling reactance is in the ratio $\frac{1}{N}$ to the plate coupling reactance.

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It should be noted here that while the fundamental amplitude of plate current, $A_1 = \frac{E}{R_p}$, the fundamental plate resistance R_p is always considerably less than the quantity $\frac{L}{RC}$. In fact, when $\frac{L}{RC}$ is large, involving large values of E, $\frac{L}{RC}$ may be ten times as great as R_p and the triode will still oscillate. This is due to the presence of the dissipative grid resistance R_g.

With electron tubes of power capacity not exceeding 50 watts, the audio-frequency bridge shown in Figure 4 furnishes a con-

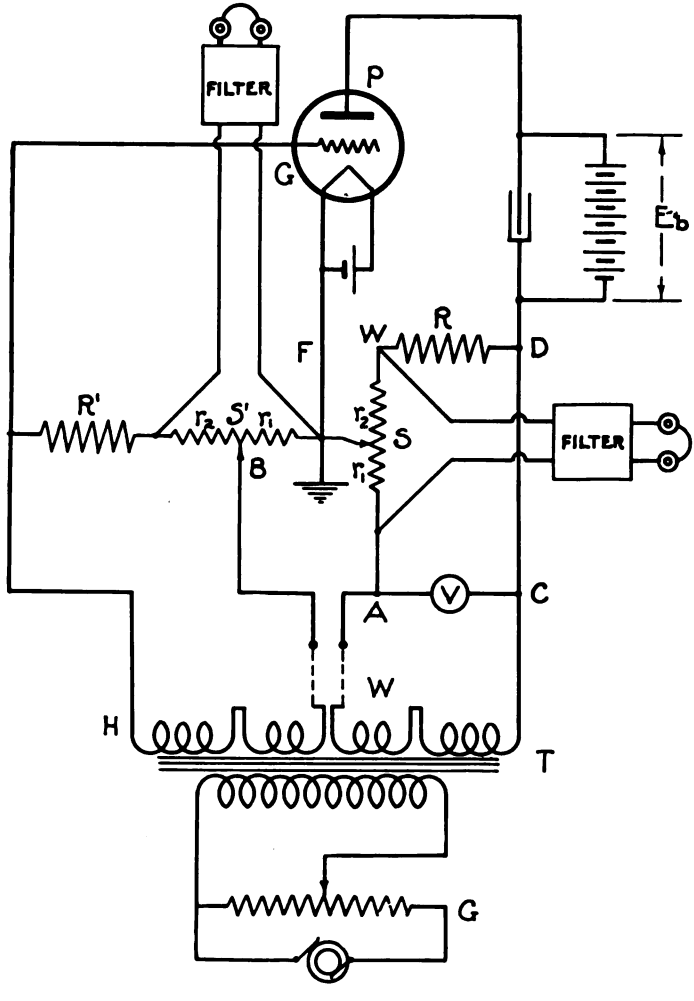

FIGURE 4—Alternating-Current Bridge

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venient method for measuring R_p and R_g for various values of E and N. A practical question intrudes itself at this point: If the power output or i^2R in a radio-frequency generating circuit depends only upon the effective resistance $\frac{L}{RC}$, and upon the plate-grid ratio, why not test a triode in a carefully designed generating circuit, of which the constants are known, obtaining P_o directly as a function of $\frac{L}{RC}$ instead of measuring R_p and R_g separately. The answer is, that the results of an audio-frequency measurement, applied to one radio-frequency circuit after another, agree, in general, more closely with measured values of the oscillating power output than do measurements on one radio-frequency circuit, when applied to circuits of a different type, or to circuits of the same type having different constants. The whole foundation upon which these computations are based is only an approximation of the true conditions. Using measurements on an oscillating triode, the computations are based upon the readings of a thermal ammeter, a circuit resistance which usually varies rapidly with the frequency, and upon the assumption of negligible extraneous capacities and negligible variations in the plate-grid ratio. The latter assumption is a departure from experimental facts only if the plate-grid ratio is decreased considerably below its optimum value, or if the alternating voltages are increased excessively above the values which yield maximum power output. But it is preferable from a practical standpoint to test a tube in a system which stimulates the conditions of an *ideal* generating system. Then the departure from these conditions may be in one direction or the other, when the triode is used as a generator, in different circuits. But at any rate the errors are not augmented by similar departures in the conditions of test.

Referring to Figure 4, the transformer T introduces into the plate and grid circuits of the triode alternating voltages having a constant ratio (which can be regulated by the switching arrangement W), and an absolute value which can be varied by the voltage divider G. The frequency is any convenient audible frequency, possibly 500 cycles. Under the influence of these voltages, currents flow in the plate circuit $A\ F\ P\ D\ C$ and in the grid circuit $B\ F\ G\ H$, which are distorted by the characteristic plate and grid harmonics. The transformer T has, however, low-resistance windings, designed to furnish alternating-current power perhaps ten times as great as the maximum power sup-

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plied in the triode. As a consequence, the 180-degree phase relation between the voltage impressed in the grid circuit and that impressed in the plate circuit is maintained at all times. In addition, these voltages e_p and e_g can be made very closely sinusoidal if the transformer is properly designed. When used with 15-watt valves, ordinary commercial 150-watt instrument transformers have been found to operate satisfactorily. On investigation with an audio-frequency oscillograph the plate and grid voltages are found to be as nearly opposite in phase as can be detected visually; also the oscillograms of either voltage, taken with full power supplied to the tube, can be superimposed upon oscillograms of the open-circuit voltages with perfect coincidence, as nearly as can be detected by the eye.

In the plate circuit, R is a resistance of 10,000 or 20,000 ohms, S is a 6-ohm slide wire, and V is an alternating current voltmeter. The filter employed with the telephones may be dispensed with entirely, for rough measurements. A two-stage audio-frequency amplifier, in which both coupling transformers are tuned to 500 cycles, eliminates the harmonics in the telephone receivers to such an extent that settings can be made on the null point of the fundamental, with a total variation (from one setting to another) of 2 per cent in the region of maximum output and 4 per cent at excessively high voltage. This is about the nearest precision measurements that are possible of achievement with electron tubes, anyway. If a wave filter is used, its "cut-off frequency" should be slightly above 500 cycles.

If E is the sinusoidal alternating voltage of frequency induced in the plate circuit, then a current I, of frequency ω and of amplitude $\frac{E}{R+r_1+r_2}$, flows around the circuit $C\ D\ W\ A$.

Thru the circuit $A\ F\ P\ D\ C$ currents of frequency ω, $2\ \omega$, $3\ \omega$, and so on, will flow, and the fundamental of amplitude A_1 has a phase of 180 degrees with respect to the current I, in the branch r_1, since the fundamental of plate current is in phase with the grid voltage and opposes the plate voltage. Hence, if the reactance of the slide-wire is small compared with the input impedance of the filter, we have as the condition for the disappearance of the fundamental note in the telephones:

$$Ir_2 = A_1 - Ir_1$$

whence, if $R_p = \frac{E}{A_1}$, then:

$$R_p = \frac{r_1 R}{r_1 + r_2} \qquad (17)$$

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In this equation the slide-wire resistance (r_1+r_2) is neglected in comparison with R.

In the grid circuit, remembering that the fundamental of grid current is in phase with the grid voltage, we have, as the condition for the disappearance of the fundamental note in the telephones

$$R_g = \frac{r_1}{r_2} R \tag{18}$$

By means of a suitable double-throw switch, the same slide-wire and filter can be used for both plate and grid measurements.

Accompanying Figure 3(a), which shows the static "oscillation characteristic" of a 5-watt valve, for $N = 1$, is Figure 3(b), showing the fundamental as power dissipated in the grid circuit of this triode, for the same value of N. The data for Figure 3(b) were obtained from measurements of R_p and R_g on the bridge shown diagrammatically in Figure 4, for different values of voltage supplied from the transformer. A complete set of measurements of this type, for a given value of N, can be made in less than a half hour's time. The separate plotted points on Figure 3(b) are the results obtained by two different operators of the bridge, taken at different times on the same value. Settings of the power bridge can be repeated with approximately the same degree of precision as can be attained in measuring the amplification factor and output resistance of an amplifier tube. Figure 3(b) shows how rapidly the grid power increases as the alternating plate voltage approaches an amplitude of 250 volts sufficient to bring it to the point Q of the characteristic. At $E = 280$ volts (root-mean-square value 200 volts) the fundamental of plate current has not yet started to decrease, and yet the grid power loss is almost sufficient to reduce the net power output to zero. The grid current is the controlling factor in small triodes.

Figure 5 shows a comparison of the results of the bridge measurements, or test, with the actual power output in a radio-frequency circuit. The heavy line shows the power output as a function of $\frac{L}{RC}$ in the oscillatory circuit, as predicted from the bridge measurement. To express the computed power as a function of $\frac{L}{RC}$ in any output circuit, equation (13) was used. The separate points on Figure 6 shows measured values of i^2R with the triode feeding an oscillatory circuit of the type shown in Figure 1. These are plotted against the impedance $\frac{L}{RC}$

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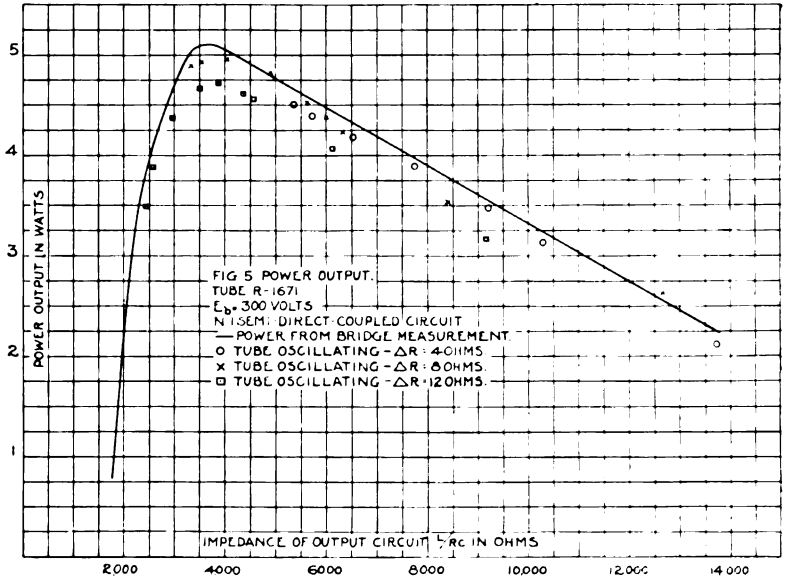
as measured on the output circuit *isolated from the tube*. No attempt was made to correct C for the triode capacities, and the



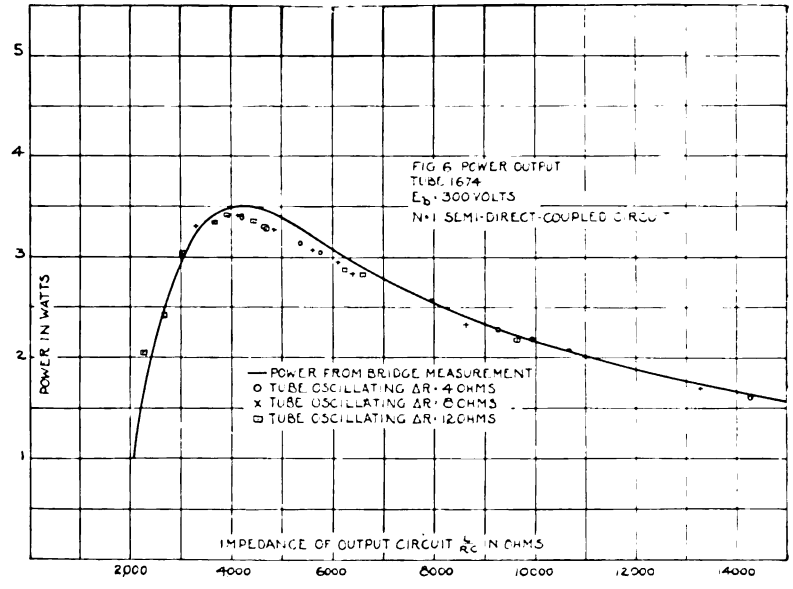


FIGURE 6

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measurements of R were made by the resistance-variation method on the L C circuit with nothing else connected to it. If a method of this sort is to be successful in practice it must be applicable with some degree of certainty to computations on antenna circuits and the like, the constants of which may be known only when they are isolated. It would be practically impossible to select a triode to operate in a given circuit, by a test of this sort, if the circuit constants had to be corrected and altered with each change in the tube or in the coupling reactances.

The absolute values of the constants of the radio-frequency circuits were as follows:

$L = 498$ microhenrys (low-frequency measurement)
$C = 0.0015$ to 0.015 microfarad

Measurements were made for three values of inserted resistance, $R = 4$ ohms, and 12 ohms. The coil, condenser and ammeter resistance added about two ohms, this being variable, of course, with the frequency.

In Figure 6 is shown for a different triode the tested power output, and actual power output as measured in the same oscillatory circuit as was used previously. The oscillation characteristic for this second triode was considerably different from that of the first one. The agreement of the predicted results with those obtained in the generating circuit is slightly better than in the previous case.

Enough experimental evidence has been obtained to indicate that this method of bridge measurement is a sufficiently close approximation, and can be performed with such a degree of facility as to make it worth while from a practical standpoint. As a matter of research it would be interesting to investigate the departures from the ideal state encountered in circuits operating at short wave lengths or with high values of R.

The writer has recently applied the bridge measurements of power output described above to radio-frequency generating circuits of two other types: the direct-coupled (Hartley) circuit, and the symmetrical iductively coupled (Meissner) circuit. The steady-state analysis of both of these systems shows that under the previously mentioned restriction (resistance of any branch of the output circuit small compared with its reactance) the voltage reaction of the output circuit upon the tube is sinusoidal over a wide operating range, and the grid and plate voltages are opposite in phase and constant in their ratio to each other. Thus the fundamental resistances of the tube as measured on the power bridge are adequate for the calculation of the alternating power

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output when the tube is associated with either of these circuits.

It is found, moreover, that in the steady state of oscillation of these circuits, as well as the semi-direct-coupled circuit, the fundamental resistance of the tube enter the expression $\frac{E^2}{P_o}$ only in *second-order terms*, E being the plate-voltage amplitude and P_o the power dissipated in the output circuit. In both cases this ratio involves only the constants of the output circuit, to first-order terms, and constitutes in effect the real (pure resistance) load in the plate circuit of the oscillating tube, containing a first-order correction for the effect of the grid current. Thus the bridge measurement for a given tube, giving power output as a function of the plate voltage, E for a given coupling ratio, can be applied as before to the calculation of the power output as a function of the constants of the output circuit by use of equations (12) and (13). For the Hartley circuit we have, to first-order terms

$$\frac{E^2}{2P_o} = \left(\frac{N}{N+I}\right)^2 \frac{L_p+L_g+2M}{RC}$$

$$N = \frac{L_p}{L_g}$$

and for the Meissner circuit:

$$\frac{E^2}{2P_o} = \frac{M_p^2}{LRC}$$

wherein R and C are the lumped inductance and capacity of the output circuit, L_p and L_g the inductance of the plate and grid coils, M the mutual inductance between the coils, L the self-inductance of the output circuit, and M_p is the mutual inductance between the plate coil and the output circuit in the Meissner arrangement.

Experiments performed with a number of 5-watt tubes have shown excellent agreement between the power output as computed from the fundamental resistance and as measured in Hartley and Meissner generating circuits having values of resiatance of from two to twelve ohms and over a range of wave lengths of from one thousand to five thousand meters. Note-Noteworthy departures of the radio-frequency i^2R in the output circuit from the computed values are encountered in the Meissner circuit only if the mutual coupling reactance be so reduced that the load departs widely from a pure resistance and the true oscillation characteristic becomes a loop instead of a single line. Even than the discrepancy in power may not be serious because the

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useful power output depends upon the *area* under the current-voltage curve, and a partial compensation occurs when the load becomes reactive. The same effect is encountered, of course, when the plate and output circuits are brought into an inductance coil thru separate taps in the Hartley circuit, or when a loosely-coupled tuned-grid arrangement is used for semi-direct coupling. In general the efficiency of conversion is decreased and the proportion of harmonics is increased when the power factor of the load is reduced appreciably below unity by the introduction of leakage reactance or of separate self-inductive reactance into the plate circuit of the tube.

The writer was given much careful and painstaking assistance in the experimental work described in this paper by H. A. Snow, of the Bureau of Standards. He is also indebted to Professor G. W. Pierce and Professor E. L. Chaffee, of Harvard University, where the experimental work was begun, for valuable suggestions.

Radio Laboratory,
Bureau of Standards,
June 14, 1922. Washington, D. C.

SUMMARY: Two new coefficients of the three-electrode tube are defined, which are significant in determining its behavior and merit as a generator of alternating currents in a highly periodic output circuit or antenna. These coefficients are based upon a simple theory of the operation of the tube as a generator and are adequate for a calculation of the power output in circuits with any type of coupling, provided certain circuital requirements are complied with which are consistent with the usual requirements of good design in radio-frequency circuits. A bridge method for measuring these coefficients is described, and experimental data upon a particular generating circuit are presented, illustrating their use in calculating the high-frequency power output.

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MATHEMATICAL TREATMENT OF RECTIFICATION PHENOMENA*

By

D. C. Prince

(General Electric Company, Schenectady, New York)

If an attempt is made to present an exact mathematical treatment of kenotron rectifier phenomena, taking account of all the factors entering in—such as transformer reactance, varying tube resistance, and so on, the expressions become so involved as to be practically almost useless. However, a very good perspective of the whole problem can be obtained by analysis of the voltage waves produced by various rectifier connections. Such waves are actually obtained at no load and in somewhat modified forms with various types of loads.

The Fourier series analysis of a half wave rectifier is:

$$e_r = E\left[\frac{1}{\pi} + \frac{1}{2}\sin\theta - \frac{2}{3\pi}\cos 2\theta - \frac{2}{\pi(m^2-1)}\cos m\theta\right]$$

where e_r is the instantaneous voltage.

E is the maximum voltage.

$e = E \sin\theta$ is the voltage before rectification.

m = any even integer.

For rectifiers utilizing two or more tubes, that is, full wave, two, three, and six or more phases, the direct current component is given by the formula

$$a_o = \frac{p}{\pi}\sin\frac{\pi}{p} \quad \text{where}$$

"p" is the number of tube phases counting single phase full wave as two, and quarter phase as four, and so on. For three and six phase, "p" is three or six, respectively.

Table I shows the direct current components of the most used simple connections.

TABLE I—*Average Direct Current Potentials*

*Received by the Editor, April 10, 1922.

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		A	B
Single phase, half wave	$1/\pi$	0.318	0.450
Single phase, full wave	$2/\pi$	0.637	0.900
Two phase	$\frac{2\sqrt{2}}{\pi}$	0.900	1.275
Three phase	$\frac{3\sqrt{3}}{2\pi}$	0.827	1.170
Six phase	$3/\pi$	0.955	1.350
Infinite phases	1	1.00	1.41

The values in column "A" are referred to the maximum voltage. Those in column "B" are referred to the nominal or mean effective voltage. From these values the tube drop must be subtracted. If there is a storage condenser across the rectifier terminals, the voltages under light load will vary from those for the phases used to the value for infinite phases at no load.

Omitting the storage condenser, the ripple voltage for any number of tube phases greater than one can be obtained from the following formula which is the result of a Fourier series analysis:

$$a_n = \frac{2\,a_o}{(n^2-1)} \quad \text{where}$$

a_n is the coefficient of the n^{th} harmonic as referred to the original alternating current frequency.

$n = Kp$ where "p" is the number of tube phases and "K" is any integer. The number of tube phases is taken as the number of anodes as in the determination of the direct current component.

Table II gives the application of this formula to the most usual rectifier combinations.

TABLE II—*Ripple Composition of Rectifier Combinations*

Coefficients of	$\cos\theta$	$\cos 2\theta$	$\cos 3\theta$	$\cos m\theta$
Single phase. (Full Wave)	$-4/3\pi$	$4/15\pi$	$4/35\pi$	$\frac{4}{\pi(4m^2-1)}$
Two phase	$\frac{4\sqrt{2}}{15\pi}$	$4\sqrt{2}/63\pi$	$4\sqrt{2}/143\pi$	$4\sqrt{2}/\pi(16m^2-1)$
Three phase	$3\sqrt{3}/8\pi$	$3\sqrt{3}/35\pi$	$3\sqrt{3}/80$	$3\sqrt{3}/\pi(9m^2-1)$
Six phase	$6/35\pi$	$6/143\pi$	$6/323\pi$	$6/\pi\,(36m^2-1)$

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For simplicity, one θ is taken as the lowest ripple frequency present in each case which is equal to the alternating current frequency multiplied by the number of tubes.

There are several other combinations which can be made up by taking two or more of the foregoing simple combinations and connecting them in series or parallel thru an interphase transformer. The resultant voltages are found by addition in the former case, while in the latter they are the average of the individual combinations. The usual combinations under this head are as follows:

Two single phase full wave rectifiers may be fed from a two-phase system and connected in series, or, thru an interphase transformer, in parallel. The average direct current voltage will be $4/\pi$ or $2/\pi$, respectively. The ripples will be the same in percentage as for an ordinary two-phase rectifier.

Three single-phase full-wave rectifiers may be fed from a three-phase system and connected in series, or, thru an interphase transformer. The voltages are $6/\pi$ and $2/\pi$, respectively, while the ripples are of the same percentages as with an ordinary six-phase rectifier.

Two three-phase rectifiers may be fed from three-phase lines in such a way as to be displaced 180° in phase and connected in series or parallel thru an interphase transformer. The voltage will be $3\sqrt{3}/\pi$ or $3\sqrt{3}/2\pi$ and the ripples will be of the same percentages as with ordinary six phase.

These special combinations have the advantage that each tube is utilized for a greater proportion of the time than with the simple connection of the same total number of phases. This results not only in both greater output and efficiency for each individual tube, but also for the high voltage transformer windings. For instance in a single phase rectifier each tube may operate up to 180°, three phase up to 120°, two phase up to 90°, six phase up to 60°. If the tube is limited in emission, the current output per tube goes up directly as the angle during which current flows. If it is limited by heating, the current output increases as the two-fifths power of this angle.

Transformer secondary capacity is always reduced when used with the usual rectifier connections. If we assume that the output current is constant, the current in any secondary transformer winding is a square wave. Suppose a 10,000-volt 10-kilowatt transformer to be used as one leg of any of the simple rectifier arrangements. The current, voltage and power outputs are shown in Table III.

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TABLE III—*Transformer Outputs with Various Rectifier Connections Based on Secondary Heating*

	Amperes	Volts Average	Fraction of a Cycle	Power	Per Cent
Non-rectifying.....	1 (r.m.s.)	10,000 (r.m.s.)		10,000	100
Single phase	1.41	9,000	0.5	6,370	64
Three phase.	1.73	11,700	0.333	6,750	68
Two phase..	2.00	12,750	0.25	6,375	64
Six phase...	2.45	13,500	0.167	5,510	55

In considering any transformer rectifier connection, it is necessary to remember that the ordinary transformer is not intended to carry direct current. A comparatively small amount of unbalanced direct current in the windings will saturate the core iron and cause heavy exciting current to be drawn, thus reducing power factor and efficiency and overheating the transformer. In a single phase half-wave rectifier, this effect is most pronounced so that this arrangement is only useful for small powers. Full-wave single phase, two phase, and six phase are normally balanced with good transformer design, so that this phenomenon requires no concern. Three-phase rectifiers have direct current components in each leg for which there must be no return magnetic circuit, if the best operation is to be secured. To meet this requirement the transformer must be core type rather than shell, and only one end of the core may be permitted to make contact with the iron of the case if the latter has any appreciable cross-section.

Before leaving the subject of transformers, it is well to consider the character of the wave which will be drawn from the alternating current supply lines. Table IV shows the harmonics which are represented by a square block of current of unit height drawn for different fractions of a cycle. Such blocks would be drawn by a rectifying transformer of low reactance feeding direct current into a highly inductive circuit. From this table the harmonics drawn by a polyphase rectifier can be made up. For instance, with a three-phase rectifier, current is drawn for one-third of the time. The second harmonic is equal to one-half of the fundamental. With the fundamentals displaced

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120° the second harmonics are displaced 240°, which is equivalent to opposite phase rotation. A second harmonic current, equal to one-half the fundamental and having opposite phase rotation, is therefore drawn from the line by a three-phase rectifier. With a six-phase rectifier, the second harmonic is nearly 87 per cent. of the fundamental, but is opposite in phase in the two legs fed from one primary phase so that no second harmonic is drawn from the line, and so on.

TABLE IV—*Harmonic Composition of Square Waves*

Fraction of Cycle.....	1/2	1/3	1/4	1/6
Direct Current Component.	0.5	0.333	0.25	0.167
Fundamental.....	0.637	0.552	0.450	0.318
2nd Harmonic.....	0	0.276	0.318	0.276
3rd "	0.212	0	0.150	0.212
4th "	0	0.138	0	0.138
5th "	0.127	0.110	0.090	0.064
6th "	0	0	0.106	0
7th "	0.091	0.079	0.064	0.045
8th "	0	0.069	0	0.069
9th "	0.071	0	0.050	0.071
10th "	0	0.055	0.064	0.055
11th "	0.058	0.050	0.041	0.029
12th "	0	0	0	0

The foregoing discussion is ideal to the extent that the transformer reactance has been neglected in all cases. The only generality that can be drawn concerning the effect of transformer reactance is that it tends to damp out higher harmonics more and more. Tube drop also has been neglected. This is a small item for high voltage work and does not affect the form of the conclusions.

In calculating the effect of smoothing networks, the harmonic analysis presents a simple method of attack which is quite exact for the case where some current is always flowing from the rectifier into the load and network. If the current is completely interrupted by the supply of all the current from a storage condenser for part of the cycle, the equations become discontinuous and the harmonic analysis no longer applies exactly. If current always flows thru one or more tubes, the impedance of the network to any ripple frequency can be ascertained and also the cur-

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rent division between network and load. It is possible to tell at a glance which harmonics appear with considerable amplitude and which need not be guarded against. It often happens that a simple aperiodic filter will care for all ripples except one and that one can then be eliminated by the use of a tuned trap, or equivalent means.

In any case a thoro appreciation of the fundamentals underlying the rectification phenomena is very useful in analyzing and interpreting the significance of experimental investigations.

SUMMARY: By Fourier series analysis of the no-load voltage waves of multiphase tube rectifiers, the direct current component, the ripple voltage of the various harmonic frequencies, the available transformer output, and the harmonic composition of the supply current are obtained and tabulated for various cases.

The effect of any unbalanced direct current component in the secondary circuit on transformer operation is described, and practical conclusions as to design are drawn. The effect of smoothing networks is considered, as well as the efficiency of utilization of the tubes in various multiphase combinations

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DISCUSSION ON "RADIO TELEGRAPHY"*

By
G. Marconi

Stuart Ballantine (by letter): Dr. Marconi's paper touches briefly upon the interesting phenomena of the propagation of electric waves over the earth's surface, especially viewed from the important geographical position of the antipole of a terrestrial source. Of special interest to me was his recorded opinion (evidently based upon directional observations made in the neighborhood of the antipole) that waves from certain American stations prefer to travel three-quarters of the earth's circumference rather than by the direct route of the great circle. Now this is a very surprising thing, and even marshalling all possible effects, coast-line diffraction, Heaviside layer reflection—and if you please, the relativity deflection due to the earth's east-west rotation—is hard to account for. In the absence of a fuller statement of the experimental conditions I do not see how it is possible to infer this from observations made at one or more closely located points, unless these points are located on the sea and the direction-finding apparatus itself is installed on a wooden raft. For experience with the radio direction-finder indicates with a high degree of probability that most of the permament deviations in direction, at least in the case of an apparatus located on land, are due to diffraction and scattering by local objects, coast lines, and so on, and that these disturbances of the approximately linear propagation do not persist at distances from their foci, which are great compared with the wave length.[1] I presume that the opinion in question is not based upon those transient shifts, studied extensively by Taylor, Kinsley, Pickard, and Loughlin in this country and by Eckersley in England, which have probably no local terrestrial genesis and are for that reason more likely to cause the large deviations which have been frequently observed. The idea that the wave consistently takes any other route than that of the great circle certainly violates

* Received by the Editor, July 18, 1922.

[1] Compare Ballantine; "The Radio Compass," page 10, and following, "Year Book of Wireless Telegraphy and Telephony," London, 1921.

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our physical intuition, and should be fortified by experimentally mapping the direction of the Poynting-vector along the entire course of propagation.

The whole matter is one of great scientific fascination, and the important practical economies made possible by the antipodal rise in signal strength impart a great interest to the theoretical problem. The spreading of waves around a spherical earth has been discussed mathematically in the important papers of Rayleigh, Macdonald, Poincaré, Nicholson, Whittaker, and others, but with considerable disagreement of results, and in most cases the discussions have failed to embody such practical features as the finite conductivity of the earth and the possible influence of the Heaviside layer. The effect of the finite earth conductivity has been considered in but one case, in a paper by Rybcynski, and if we accept the experimental evidence lately submitted by Eckersley as to the existence of a super-atmospheric conducting stratum, the approximate influence of this may be treated by a method of Macdonald's[2] for the oscillations in simply-connected spaces. I have carried this calculation thru, assuming perfect earth conductivity, and have obtained formulas which with the complete experimentally determined attenuation law may help to fix the possible height of this reflecting layer. But in view of the great difficulty of the problem, augmented by the impossibility of taking into the mathematical equations all the practical deviations from the idealized problem, I think that practical men will welcome the experimental data promised by Dr. Marconi with considerable satisfaction. It would be especially interesting to know if Fresnel nodal-lines are discovered, and whether the vibrations conspire sufficiently to give an antipodal rise of the order of the theoretical calculations.

[2] Compare H. M. Macdonald; "Electric Waves," page 49 and following, Cambridge, 1902.

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DIGEST OF UNITED STATES PATENTS RELATING TO RADIO TELEGRAPHY AND TELEPHONY*

ISSUED JUNE 27, 1922–AUGUST 22, 1922

BY

JOHN B. BRADY

(PATENT LAWYER, OURAY BUILDING, WASHINGTON, D. C.)

1,420,629—J. H. Hammond, Jr., filed March 29, 1918, issued June 27, 1922.

TELEDYNAMIC ORIENTATION SYSTEM, wherein a transmitting station is arranged to vary the frequency of radiated impulses from time to time in proportion to the space thru which the controller at the transmitter is moved and a receiving apparatus having a controller arranged to move over a variable path in response to transmitted impulse for local control of circuits in accordance with transmitted impulses.

1,420,824—H. P. Donle, filed May 31, 1921, issued June 27, 1922.

RECTIFIER, comprising a tube containing two cold electrodes within a vacuum. The electrodes are shaped and arranged so that negative particles tending to leave an electrode or move away from its vicinity will move in a line substantially at right angles to the electrode surface giving a predominating one-way transmission and consequently the quality of rectification.

1,421,015—M. C. Latour, Paris, France, filed April 18, 1916, issued June 27, 1922.

A TELEPHONE having a diafram provided with slits extending in a direction from pole to pole in the diafram for reducing eddy current losses.

1,421,447—Le Roy Kelsay, New York, N. Y., assignor to Western Electric Company. Filed February 8, 1921, issued July 11, 1922.

SWITCHING KEY.

*Received by the Editor, September 6th, 1922.

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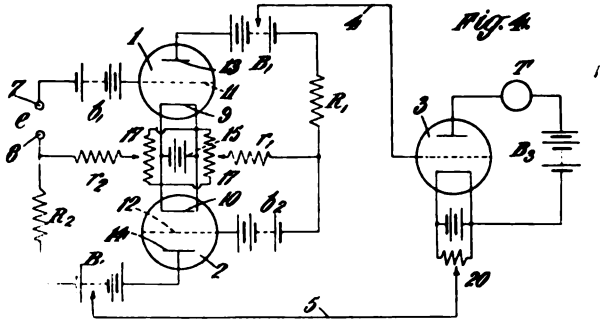
1,422,013—L. B. Turner, filed February 6, 1920, issued July 4, 1922.



NUMBER 1,422,013—Thermionic Apparatus Applicable for Radio Telegraphy and Other Purposes

THERMIONIC APPARATUS APPLICABLE FOR RADIO TELEGRAPHY AND OTHER PURPOSES, having a circuit arrangement of two electron tubes. The circuit comprises connections between the anode and filament and grid and filament of each tube, a battery for supplying current to each of the circuits, and a common branch connection containing high resistance in the anode and grid circuits of both tubes whereby the anode of one tube and the grid of the second tube in said apparatus are connected, and the anode of said second tube and the grid of the first-mentioned tube are connected, to form a closed circuit cascade system. Increased amplification by resistance retroactions is claimed for this circuit.

1,422,312—F. S. Smith, filed February 12, 1922, issued July 11, 1922. Assigned to The Products Protection Corporation.

ELECTRIC CONDENSER, constructed in tubular form containing as a dielectric a gas such as nitrogen, carbon dioxide, or air permanently sealed. An extended round rod forms one armature of the condenser and a concentric tube the opposite armature thereof.

1,422,429—C. D. Filikins, Schenectady, New York, assignor to General Electric Company. Filed April 21, 1919, issued July 11, 1922.

CONNECTION FOR ELECTRICAL APPARATUS, particularly designed for bringing out connections from the inner rotatable coil of a variometer or variocoupler.

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1,422,837—I. B. Crandall, Nahant, Massachusetts, assignor to Western Electric Company. Filed October 13, 1917, issued July 18, 1922.

Connecting Transmitters to Vacuum Tube Amplifiers.

1,422,882—H. W. Nichols, filed September 1, 1915, issued July 18, 1922. Assigned by mesne assignments to Western Electric Company, Incorporated.

Radio Transmission. This invention relates to a modulation circuit for a transmitter. The modulator tube is inserted as a shunt upon an impedance in the antenna which is comparable with that of the tube so that only one-half or a small portion of the antenna power is thereby carried by the modulator tube.

1,423,345—D. G. McCaa, filed May 20, 1921, issued July 18, 1922. Assigned one-half to Cornelius D. Ehret, of Philadelphia, Pennsylvania.

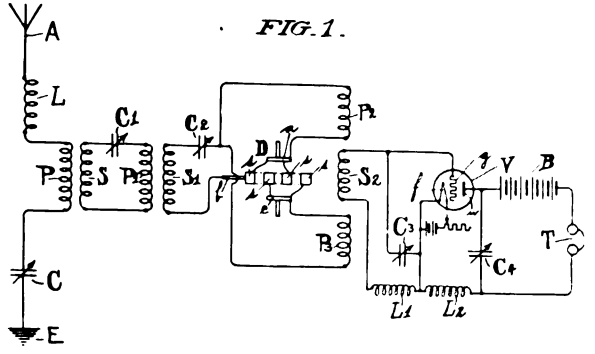

FIG. 1.

Number 1,423,345—Signaling Method and Apparatus

Signaling Method and Apparatus for receiving radio signals. A local oscillator is employed for generating oscillations of a frequency equal to the frequency of the received signal oscillations. A rotating commutator is used periodically to reverse the coaction of the received and locally produced oscillations at an audible frequency and the resultant impressed upon a detector and telephone receivers. The production of beats is avoided.

1,424,065—Edwin H. Armstrong, filed June 27, 1921, issued July 25, 1922.

Signaling System. This is the patent on the Armstrong super-regenerative circuit. Twelve diagrams are shown for con-

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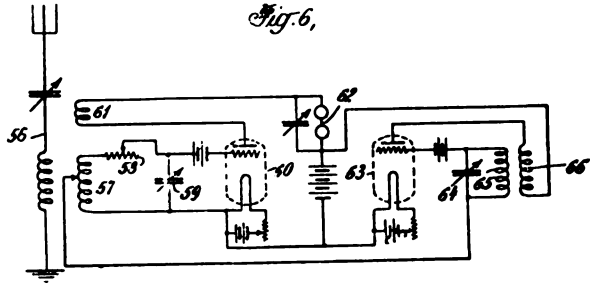
necting electron tube circuits in different ways for securing super-regeneration. The electron tube is connected for regenerati n and the circuit adjusted to its maximum sensitiveness. Then the relation between the amount of feedback action and t damping is periodically varied over a certain minimum range a a state of equilibrium produced in which super-regeneratio n obtained.



NUMBER 1,424,065—Signaling System

1,324,091—C. R. Fountain, filed January 21, 1919, issued July 25, 1922.

RADIO ELECTRON OSCILLATOR. A cylindrical construction of tube is shown in this patent intended for high power operation.

1,424,141—L. F. Fuller, filed June 16, 1919, issued July 25, 1922. Assigned to Augustus Taylor, of San Francisco, California.

ELECTRICAL OSCILLATION GENERATOR. The patent relates to an anode tip for an arc transmitter. The tip comprises a U-shaped hollow metallic tube thru which cooling water may circulate while the arc discharges from the outer surface of the tube.

1,424,294—S. G. Frost, filed May 11, 1922, issued August 1, 1922.

SIGNALING UNIT FOR RADIO TELEGRAPHY, comprising a magneto electric generator for furnishing direct current for operation of a radio transmitter. An automatic switch is operated by the rotation of the armature shaft for closing the transmitter circuit in a desired sequence.

1,424,365—E. H. Loftin and H. H. Lyon, filed April 5, 1920, issued August 1, 1922.

RADIO SIGNALING. This patent relates to an arrangement of antenna in a low horizontal system. A plurality of low hori-

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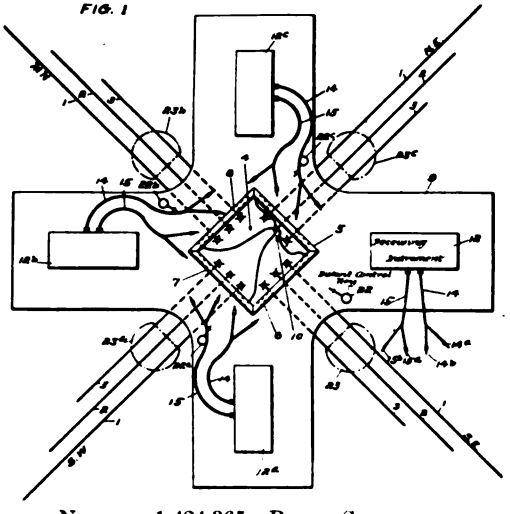
zontal wires of different lengths are extended in different directions and connected with a selector board whereby a receiver may be connected to any number of the wires to choose the components or combinations of components which give the desired optimum antenna length and direction for reception.



NUMBER 1,424,365—RADIO SIGNALING

1,424,515—John Parkin, Jr., filed April 25, 1921, issued August 1, 1922.

RHEOSTAT having a rotatable graduated dial and a variable resistance element circularly disposed around the back of the dial for contact with a stationary terminal.

1,424,641—J. H. Hammond, Jr., filed December 23, 1918, issued August 1, 1922.

MARINE TRAILER FOR RADIANT-ENERGY RECEIVING SYSTEMS. This patent shows a form of trailer adapted to be automatically detached from a projected body such as a torpedo for extending an antenna conductor out behind the torpedo for radio control of mechanism within the torpedo.

1,424,805—L. De Forest, filed June 16, 1917, issued August 8, 1922.

SUBTERRANEAN SIGNALING SYSTEM, in which overhead conductors 20 and 21 are extended out on pole lines and dropped vertically to plates 3 and 4 buried in the earth in a conductive

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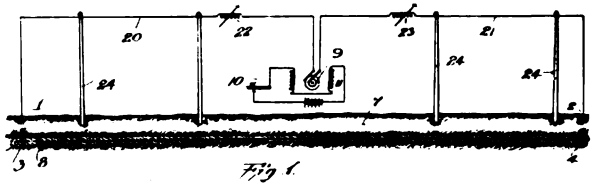
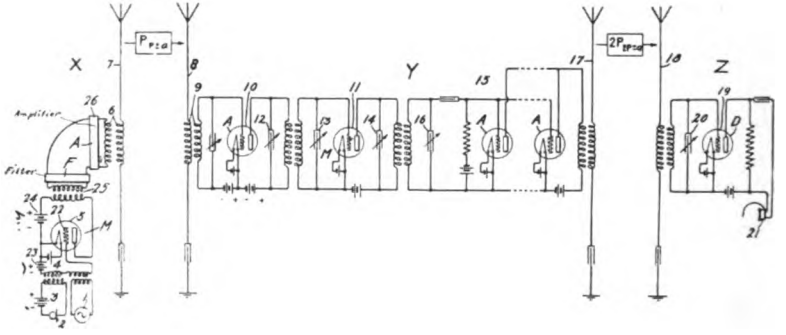
strata below the surface of the earth. The radio apparatus is connected with the overhead system.



NUMBER 1,424,805—Subterranean Signaling System

1,424,866—P. I. Wold, filed February 17, 1917, issued August 8, 1922. Assigned to Western Electric Company, Incorporated.



NUMBER 1,424,866—Method and Means for Relaying Modulated Carrier Waves

METHOD AND MEANS FOR RELAYING MODULATED CARRIER WAVES, wherein a transmitting station is arranged to control a repeating station having a receiving circuit connected to modulate a transmitter which transmitter retransmits the signal energy to a more distant receiver. The patent is directed to a circuit arrangement for eliminating the tendency of the system to "sing."

1,425,154—R. A. Weagant, filed December 13, 1917, issued August 8, 1922. Assigned by mesne assignments to Radio Corporation of America.

APPARATUS FOR RECEIVING RADIO SIGNALS, including a screened loop antenna shielded from static disturbances. An inverted trough screen covers the loop above and an adjustable circuit provided for connecting the screen to earth.

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Fig. 1.

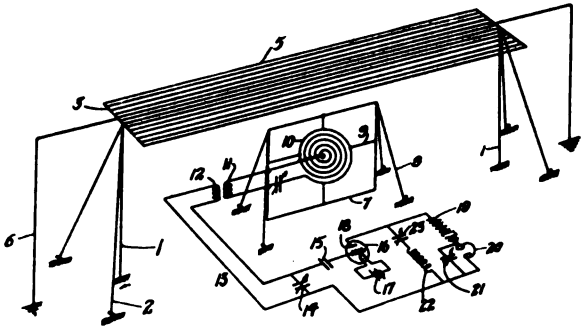
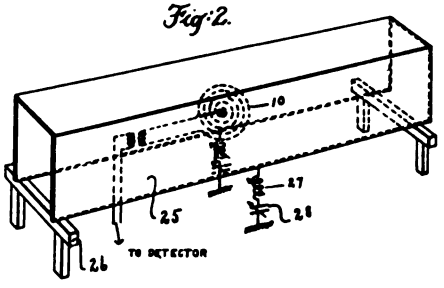


Fig. 2.



NUMBER 1,425,154—Apparatus for Receiving Radio Signals

1,425,522—J. H. Hammond, Jr., filed June 7, 1917, issued August 15, 1922.

SYSTEM FOR SOUND TRANSMISSION, wherein a receiver circuit is used with separate radio controls for generating and transmitting submarine sound signals of different frequencies in accordance with radio signals transmitted from a distant station.

1,425,523—J. H. Hammond, Jr., filed June 22, 1917, issued August 15, 1922.

TRANSMISSION SYSTEM FOR RADIANT ENERGY, wherein a central radio transmitting station is arranged to have its circuits closed by line wire from any one of a plurality of different stations with an indicator at each of the central stations connected by the same wires which form the radio control circuit to advise the operator whether or not the radio transmitter is properly functioning.

1,425,912—R. T. Staples, filed August 17, 1920, issued August 15, 1922. Assigned to Western Electric Company, Incorporated.

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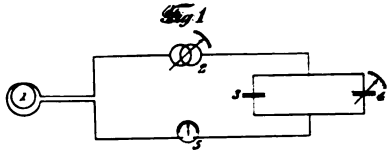
CONDENSER AND THE METHOD OF MAKING SAME. The condenser unit of this invention is impregnated with paraffin having a solidifying temperature of 120° F. (48.9° C.) and heated to a temperature of approximately 110° F. (43.3°C.) and maintained at such temperature for a period of not less than three hours.

1,426,132—F. N. Waterman, filed March 23, 1917, issued August 15, 1922. Assigned by mesne assignments to Radio Corporation of America.



NUMBER 1,426,132—Electrical Measuring Instrument

ELECTRICAL MEASURING INSTRUMENT for the direct reading of decrement of a circuit. The instrument comprises a pick-up inductance coil 1, a variometer 2 shielded from inductance 1, a fixed condenser 3, and variable condenser 4 and a current-squared meter 5. The instrument is designed after Bjerknes' formula relating to the decrements of two loosely coupled circuits as follows:

$$\delta_1+\delta_2=2\pi\left(1-\frac{n_r}{n_1}\right)\sqrt{\frac{I_1^2}{I_r^2-I_1^2}}$$

where:

δ_1 = decrement of circuit under test per cycle.
δ_2 = decrement of circuit of instrument per cycle.
n_r = frequency at resonance.
n_1 = frequency off resonance.
I_r^2 = current squared at resonance.
I_1^2 = current squared off resonance.

In operation the condenser 4 is set to its zero or minimum value.

The coil is placed in inductive relation with the exciting circuit, but the variable inductance 2 screened from such action. For this purpose the coil 1 is preferably separate from the rest of the apparatus, but connected thereto by a flexible cable of sf-u ficient length so that, while coil 1 is in inductive relation, the

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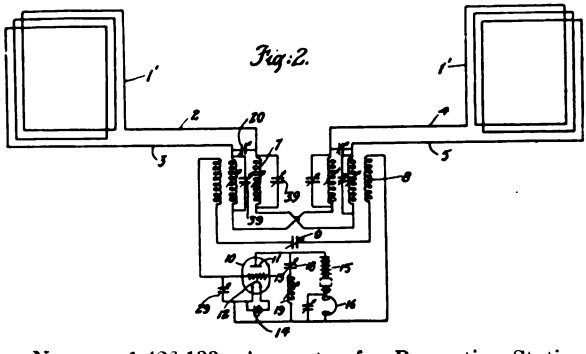
variable inductance, is sufficiently distant to escape any appreciable influence. The meter circuit is then adjusted to resonance by the variometer 2 and the maximum value I_r^2, of the square of the current noted. The variometer is again adjusted, by decreasing the inductance 2, until the current squared is one-half its resonance value. The variometer is left in this last position.

It will be seen that these operations have been conducted with a fixed value of capacity and that the operations necessary to determine the value of the radical in the equation of Bjerknes have been performed. Hence, if the capacity be now changed so as to alter the wave length of the circuit to the other side of the resonant value until I_r^2 is again equal to one-half I_r^2, for the new value of capacity, C_2, there will be but one value of the equation for $\delta_1+\delta_2$. Hence, if the value of condenser 3 is known, and 4 is a calibrated condenser, a scale for $\delta_1+\delta_2$ can at once be calculated, calibration by comparison being unnecessary. Such a scale, graduated in terms of decrement, is directly attached to condenser 4 and when the adjustment for I has been made by means of 4, the sum $\delta_1+\delta_2$ can be read directly from this scale. The instrument is thus direct reading.

1,426,133—R. A. Weagant, filed December 12, 1917, issued August 15, 1922. Assigned by mesne assignments to Radio Corporation of America.



NUMBER 1,426,133—Apparatus for Preventing Static Interference in Radio Signaling

APPARATUS FOR PREVENTING STATIC INTERFERENCE IN RADIO SIGNALING, comprising a pair of loop collectors mounted vertically and spaced horizontally a fraction of a wave length. A receiving current is provided whereby impulses or electromotive

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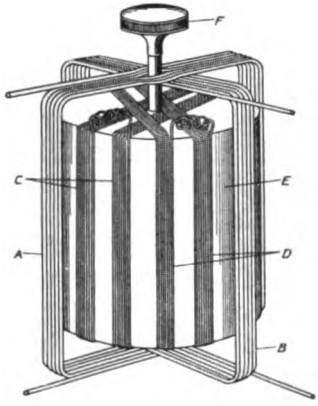
forces set up in the collectors simultaneously, as by static disturbances, are made to oppose each other while oscillations set up by signal waves, being out of phase, act cumulatively on the detector.

1,426,137—G. N. Wright, filed April 16, 1921, issued August 15, 1922. Assigned to Radio Corporation of America.



NUMBER 1,426,137—Radio Goniometer

RADIO GONIOMETER constructed with antenna coils *A* and *B* and search coils *C* and *D*, each consisting of two windings at an acute angle to the other set.

1,426,337—E. A. Sperry, filed July 9, 1917, issued August 15, 1922.

SIGNALING APPARATUS FOR DETECTING SUBMARINES, comprising a system of submarine nets in which a submerged submarine might become entangled with the succeeding carrying away of the net whereupon buoys, normally submerged and anchored, are released and rise to the surface. The buoy contains a complete radio transmitting equipment. The rising of the buoy automatically starts the transmitter, which functions to radiate a particular set of signals enabling a radio direction-finder aboard ships in vicinity to determine the position of the submarine for pursuit.

1,426,465—E. G. Danielson, San Francisco, California, assignor to Elmer T. Cunningham, San Francisco, California. Filed February 14, 1921, issued August 22, 1922.

VARIABLE RESISTANCE, comprising a molded mixture of a finely divided conducting material and a synthetic gum which

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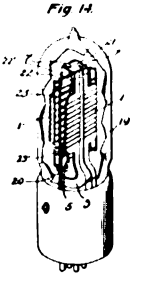
hardens in molding. Contacts are provided along the resistance element whereby its value is made variable by steps.

1,426,516—L. Steinberger, Brooklyn, N. Y., filed April 29, 1918, issued August 22, 1922.

INSULATOR.

1,426,734—W. F. Hendry, filed April 30, 1919, issued August 22. 1922. Assigned to Western Electric Company, Incorporated.



NUMBER 1,426,734—Method of Manufacturing Audions

METHOD OF MANUFACTURING AUDIONS, which avoids the use of glass arbor or stem for supporting the electrodes. The plates of this tube are cut from a blank with a collar portion arranged to embrace the glass support in the tube. A metallic box-like connection for the top of the plates carries insulated material forming a support for the other electrodes.

1,426,743—F. J. Kaehni and W. L. Kaehni, Cleveland, Ohio, filed June 9, 1922, issued August 22, 1922.

ELECTROMAGNETIC SOUND-PRODUCING DEVICE for operation with a radio receiving apparatus. An arrangement of magnets is provided whereby a vertical armature is vibrated transversely in accordance with the telephonic signal energy in the plate circuit of the last tube. A depression in the end of the armature receives a phonograph stylus imparting mechanical vibrations to the diafram thereof and reproducing the signals through the usual phonograph horn.

1,426,751—P. K. McCall, West Orange, N. J., and H. R. Menefee, New York, N. Y., assignors to Western Electric Company, Incorporated. Filed August 13, 1919, issued August 22, 1922.

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THERMIONIC REGULATOR for controlling the potential of an air fan generator for aircraft radio apparatus. An electron tube circuit is provided for regulating the potential. The electron tube is mounted within the stream line casing of the generator.

1,426,754—R. C. Mathes, New York, N. Y., assignor to Western Electric Company, Incorporated. Filed October 23, 1916, issued August 22, 1922.

CIRCUITS FOR ELECTRON DISCHARGE DEVICES.

1,426,755—R. C. Mathes, New York, New York, and S. Read, East Orange, New Jersey, assignors to Western Electric Company, Incorporated. Filed May 9, 1919, issued August 22, 1922.

VACUUM-TUBE CIRCUITS AND METHODS OF OPERATING THEM.

1,426,801—W. Wilson, filed March 21, 1917, issued August 22, 1922. Assigned to Western Electric Company, Incorporated.

REPEATER FOR UNDULATORY CURRENTS, constructed to increase the amplifying power of a tube and prevent the formation between the anode and cathode of an arc or glowing discharge characteristic of positive ionization. An apertured screen is mounted in the space between the cathode and anode and charged positively, increasing the thermionic discharge of thec athode.

1,426,807—H. D. Arnold and J. P. Minton, East Orange, New Jersey, assignors to Western Electric Company. Filed November 12, 1917, issued August 22, 1922.

METHOD AND SYSTEM FOR TESTING TRANSMITTERS OR RECEIVERS.

1,426,788—L. Steinberger, Brooklyn, N. Y., filed November 26, 1918, issued August 22, 1922.

INSULATOR STRAIN MEMBER.

1,426,789—L. Steinberger, Brooklyn, N. Y., filed January 28, 1922, issued August 22, 1922.

INSULATOR.

1,426,826—H. C. Egterton, filed July 19, 1917, issued August 22, 1922. Assigned to Western Electric Company, Incorporated.

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ELECTRON DISCHARGE DEVICE CIRCUITS, arranged for the elimination of excessive positive charges on the grids with inherent "blue haze." A leakage path to the filament is provided for the excess positive charges on the grid either by an auxiliary electrode within the tube or by a two-electrode tube connected externally across the grids and filament electrodes of the tube.

1,426,944—E. F. W. Alexanderson, filed September 4, 1917, issued August 22, 1922. Assigned to General Electric Company.

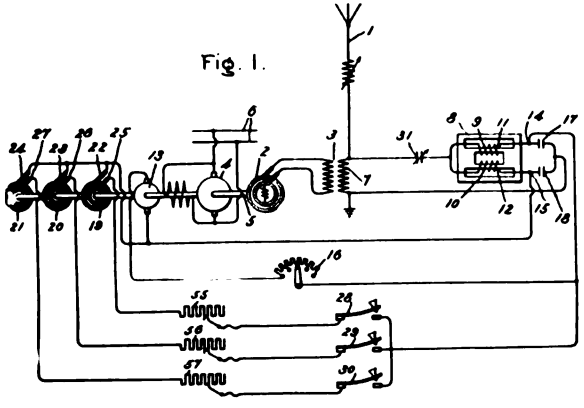

Fig. 1.

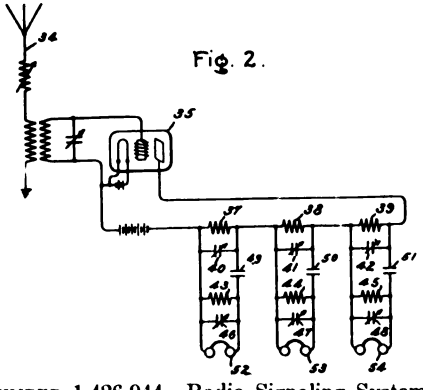

Fig. 2.

NUMBER 1,426,944—Radio Signaling System

RADIO SIGNALING SYSTEM for multiplex transmission and reception on the same wave length. A radio frequency alternator is employed at the transmitter with the antenna current controlled by a magnetic amplifier. A plurality of different audio frequency generators are connected thru separate key circuits with the control winding of the magnetic amplifier. In trans-

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mitting simultaneously by the separate key circuits the amplitude pulsations produced in the fundamental wave will be the resultant or combination of the amplitude pulsations produced by the several different frequencies employed. At the receiver the antenna is tuned to the fundamental frequency. A secondary receiving circuit is employed with branch circuits, each tuned to the particular frequency of the amplitude pulsations used in the corresponding key circuit at the transmitter.

Partial List of Registered Radio Trademarks

In response to several requests more data is given on those marks published in the list appearing in the August, 1922, issue. A trademark registration remains in force for a period of twenty years with privilege of renewal for similar periods upon the expiration of those periods, by payment of fees prescribed by law.

113,751—"Lenzite," for electromagnatic wave detectors or other electrical devices for receiving or conveying sound waves. Lenzite Crystal Corporation of Pasadena, California. Registered October 31, 1916.

129,698—"Radio Amateur News" for magazines published monthly. Experimenter Publishing Company of New York. Registered March 9, 1920.

140,120—"Radio News" for publications issued monthly. Experimenter Publishing Company of New York. Registered March 8, 1921.

134,313—"Radiophone" for radio apparatus. De Forest Radio Telephone and Telegraph Company of New York. Registered August 24, 1920.

134,314—"Radiofone" for radio apparatus. De Forest Radio Telephone and Tehegraph Company of New York. Registered August 24, 1920.

150,948—"Radiotron" for electron tubes and valves. Radio Corporation of America. Registered January 10, 1922.

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134,881—Diagrammatic arrangement of circles with design within the inner circle for telephones and parts thereof. American Thermophone Company, Boston, Massachusetts. Registered September 21, 1920.

152,961—"RADIOLA" for radio apparatus. Radio Corporation of America. Registered March 7, 1922.

153,172—"RADIO MFG. CO." (Mark arranged within a triangular ornamentation) for radio apparatus. Joseph D. R. Freed, of New York. Registered March 14, 1922.

153,238—Representation of Magnavox Loud Speaker with lion head protruding from horn, for loud speaking telephones and other amplifying reproducers. The Magnavox Company, Oakland, California. Registered March 14, 1922.

155,802—"U V 200" for vacuum tubes and valves. Radio Corporation of America. Registered June 6, 1922.

155,803—"U V 201" for vacuum tubes and valves. Radio Corporation of America. Registered June 6, 1922.

155,804—"U V 202" for vacuum tubes and valves. Radio Corporation of America. Registered June 6, 1922.

155,805—"U V 203" for vacuum tubes and valves. Radio Corporation of America. Registered June 6, 1922.

156,671—"VOCALOUD" for loud speakers. John Firth and Company of New York. Registered July 11, 1922.

156,630—"SUPERPHONE" for telephones. G. Boissonnault Company. Registered July 11, 1922.

156,693—"ABC STANDARDIZED RADIO" for radio apparatus. Jewett Mfg. Corporation. Registered July 11, 1922.

156,781—"AERIOLA JUNIOR" for radio apparatus. Westinghouse Electric and Mfg. Co. Registered July 11, 1922.

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The following trademarks have been published in the Official Gazette of the Patent Office and unless a notice of opposition is filed within thirty days after the publication, the marks will be registered in the regular course of business. A notice of opposition is simply an opportunity for others legally to contest the registration who may believe that the trademark sought to be registered is substantially identical with a trademark previously used upon goods of the same descriptive qualities; or that a similar registration has been previously made for that same mark by another; or that the mark so nearly resembles such a trademark or known trademark owned or used by another as to be in conflict therewith and void; or that the business of another might be unjustly injured by the registration of such a trademark with its inherent legal force.

It, therefore, behooves members vitally interested in the business of radio to watch the publications of trademarks to eliminate legal difficulties. The numbers given in the following list are serial numbers of pending applications:

159,777—"AIR O PHONE" for radio apparatus. Air-o-phone Corporation, New York, N. Y., claims use since February 9, 1922. Published May 9, 1922.

161,242—"E" arranged with ornamental design for radio apparatus. Everett Electric Corporation, New York, N. Y., claims use since March 21, 1922. Published July 18, 1922.

162,616—"EDELMAN RAYTAINOR" for radio apparatus. Philip E. Edelman, of New York, claims use since August 1, 1921. Published July 18, 1922.

162,669—"R. I. Co." Letters arranged in the form of filament, grid and plate electrodes of an electron tube. Brent Daniel Radio Instrument Company, Incorporated, of Washington, D. C., claims use since September 1, 1920. Published July 18, 1922.

163,422—"RADIO BROADCASTING NEWS" for publications. Westinghouse Electric and Mfg. Co., East Pittsburgh, Pennsylvania, claims use since December 29, 1921. Published August 1, 1922.

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163,455—"ETHEROLA" in ornamental design for radio receiving apparatus. Ralph A. McKinney, Pittsburgh, Pennsylvania, claims use since February 1, 1922. Published August 15, 1922.

164,117—"LISSENIN" for radio apparatus. Louis L. Rappaport-Lissenin Radio Parts Co., Ridgefield Park, New Jersey, claims use since January 20, 1922. Published August 15, 1922.

164,249—"RADIO WORLD" for publications. Roland B. Hennessy-Radio World Co., New York, N. Y., claims use since April 1, 1922. Published August 15, 1922.

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164,833—"RADIOLETTE" for vacuum tubes and valves. Radio Corporation of America claims use since May 27, 1922. Published August 15, 1922.

165,195—"RADIO BUILDER" for magazines. Raymond Kanofsky Radio Builder Publishing Co., New York, N. Y., claims use since June 6, 1922. Published August 15, 1922.

165,321—"VOCAROLA" for loud speakers. Westinghouse Electric

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and Mfg. Co., East Pittsburgh, Pennsylvania, claims use since December 1, 1921. Published August 15, 1922.

165,657—"RADIOSTAT" for compression resistor carbon pile rheostats. Allen-Bradley Co., Milwaukee, Wisconsin, claims use since April 1, 1922. Published August 15, 1922.

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PROCEEDINGS OF

The Institute of Radio Engineers

Volume 10 DECEMBER, 1922 Number 6

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RECEIVING MEASUREMENTS AND ATMOSPHERIC DISTURBANCES AT THE NAVAL RADIO RESEARCH LABORATORY, BUREAU OF STANDARDS, WASHINGTON, JULY AND AUGUST, 1922*

By

L. W. Austin

(United States Naval Radio Research Laboratory, Washington, D. C.

(Communication from the International Union for Scientific Radio Telegraphy)

The following tables give the field intensities produced at this laboratory by the Lafayette and Nauen stations, and the corresponding strength of the atmospheric disturbances during July and August. The method of measurement has been already described.[1]

The calculated intensities for the signals assuming 480 amperes at Lafayette and 380 amperes at Nauen are

$$E \text{ (Lafayette)} = 31.5 \cdot 10^{-6} \text{ volts/meter}$$
$$E \text{ (Nauen)} = 15.3 \cdot 10^{-6} \text{ volts/meter}$$

It is seen that the observed morning values for the intensities are a little more than twice the calculated values, while the afternoon values, probably due largely to local fading, fall far below the calculated. The average ratios of afternoon values to morning values in July are for Lafayette 0.22 and Nauen 0.18, and, for August, Lafayette 0.32 and Nauen 0.24. The average ratios of signals to disturbances, in July, are for Lafayatte in the morning 0.42, in the afternoon 0.045; and for Nauen in the morning 0.73 and in the afternoon 0.032.

In August the signal disturbance ratio is for Lafayette 1.05 in the morning, and in the afternoon 0.075. For Nauen it is 0.58 in the morning, and 0.035 in the afternoon. In July, Lafayette faded five times so as to be unmeasurable, while Nauen becomes unmeasurable seven times and was not heard at all three

*Received by the Editor, October 5, 1922.

[1] Proceedings of The Institute of Radio Engineers, 1922, part 3, pages 153 and 239.

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times. Of course, it is impossible to say that Nauen was transmitting at these times, tho the signals were listened for during more than an hour. In August, Lafayette faded four times below the measurable value; while Nauen faded five times and was not heard seven times.

FIELD INTENSITY OF LAFAYETTE AND OF DISTURBANCES ($\lambda = 23{,}400$ m.) IN JULY, 1922, IN MICRO-VOLTS PER METER

	10 A. M.		3 P. M.	
Date	Signal	Disturbances	Signal	Disturbances
1	*	300	....	....
3	100.0	100	**	1,000
5	90.0	150	30.0	560
6	100.0	150	20.0	680
7	100.0	200	25.0	450
8	75.0	300	20.0	450
10	*	80	**	1,000
11	80.0	200	15.0	680
12	100.0	300	20.0	600
13	*	80	20.0	400
14	90.0	100	**	800
15	75.0	200	....	....
17	100.0	200	....	....
19	80.0	150	20.0	300
20	75.0	200	**	500
21	50.0	300	**	600
22	60.0	200	....	....
25	75.0	150	30.0	300
26	90.0	200	35.0	400
27	60.0	150	35.0	300
29	90.0	300	....	....
31	60.0	200	30.0	300
Average	81.6	191	17.6	548

**Too weak to measure.
*Not heard.
....Not taken.

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FIELD INTENSITY OF NAUEN AND OF DISTURBANCES ($\lambda = 12{,}500$ m.) IN JULY, 1922, IN MICRO-VOLTS PER METER

	10 A. M.		3 P. M.	
Date	Signal	Disturbances	Signal	Disturbances
1	34.0	50	**	....
3	56.0	60	*	800
5	30.0	50	13.0	200
6	51.0	40	**	600
7	34.0	50	8.0	500
8	30.0	60	....	400
10	34.0	40	8.0	600
11	30.0	30	10.5	800
12	30.0	50	**	500
13	43.0	60	**	200
14	30.0	50	8.0	300
15	*	60	*	....
17	34.0	30	....	....
19	51.0	60	13.0	100
20	34.0	50	**	200
21	30.0	40	**	300
22	34.0	50	....	....
25	34.0	60	16.0	200
26	43.0	80	13.0	200
27	*	60	*	150
29	43.0	80	....	....
31	30.0	60	13.0	200
Average	37.2	50.8	6.4	36.8

**Too weak to measure.
*Not heard.
....Not taken.

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FIELD INTENSITY OF LAFAYETTE AND OF DISTURBANCES ($\lambda = 23{,}400$ m.) IN AUGUST, 1922, IN MICRO-VOLTS PER METER

	10 A. M.		3 P. M.	
Date	Signal	Disturbances	Signal	Disturbances
1	100.0	100	50.0	300
2	65.0	200	50.0	200
3	60.0	150	45.0	300
4	80.0	150	**	....
5	100.0	80	**	1,000
7	65.0	100	....	....
8	40.0	200	25.0	500
9	50.0	300	40.0	200
10	60.0	200	15.0	300
11	75.0	200	20.0	400
12	70.0	150	....	....
14	60.0	200	15.0	200
15	50.0	80	10.0	1,000
16	75.0	100	**	1,000
17	75.0	80	25.0	300
18	60.0	100	....	....
19	45.0	100	**	....
21	100.0	80	30.0	150
22	75.0	60	20.0	300
23	50.0	20	**	1,000
24	100.0	30	**	800
25	75.0	40	....	....
26	75.0	60	....	....
28	50.0	300	25.0	800
29	75.0	20	20.0	600
Average	69.2	124	20.5	519

**Too weak to measure.

*Not heard.

....Not taken.

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FIELD INTENSITY OF NAUEN AND OF DISTURBANCES ($\lambda = 12{,}500$ m.) IN AUGUST, 1922, IN MICRO-VOLTS PER METER

	10 A. M.		3 P. M.	
Date	Signal	Disturbances	Signal	Disturbances
1	26.0	100	**	500
2	30.0	80	**	1,000
3	30.0	80	8.0	800
4	26.0	60	**	600
5	34.0	40	....	....
7	43.0	30	16.0	300
8	34.0	60	8.0	600
9	30.0	20	*	100
10	30.0	60	*	100
11	26.0	40	10.5	300
12	34.0	40	....	....
14	38.0	80	16.0	200
15	34.0	60	**	400
16	30.0	60	**	200
17	34.0	40	16.0	150
18	26.0	50	*	200
19	30.0	80	13.0	300
21	30.0	60	....	....
22	26.0	80	*	....
23	34.0	60	*	400
24	17.0	1,000	*	300
25	*	1,000	*	2,000
28	38.0	80	13.0	200
29	36.0	150	13.0	150
Average	31.1	131	12.6	440

**Too weak to measure.

*Not heard.

....Not taken.

SUMMARY: The intensities of the signals from the Lafayette and Nauen stations during July and August, 1922 are given, together with the simultaneous static intensities. A comparison of the calculated and actual strengths is also given.

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RADIO RECEIVING EQUIPMENT*

By

Frank Conrad

(Assistant Chief Engineer, Westinghouse Electric and Manufacturing Company, Pittsburgh, Pennsylvania)

This paper is intended to discuss questions of design of those types of receiving apparatus which are adapted for reception over a limited range of wave length, and which depend for their operation on such manipulation as can be successfully carried out by persons entirely unfamiliar with the technique of radio apparatus. Their principal field of application is the reception of broadcast radio telephone signals.

Among the many requirements which an ideal receiver of this class should fulfil are that:

(1) It should tune in the wave length desired with only simple adjustments, which should not interact on each other. With a signal of normal audibility from a desired station, the signal strength from another equal or possibly more powerful station, separated by ten thousand cycles, should be below audibility.

(2) Its sensitivity should be such that its range will be limited by static interferences, fading, and so on, rather than by actual lack of response. Any local sources of power necessary for its operation should require infrequent attention.

The first-mentioned requirement, which may be termed selectivity, is more or less fulfilled by giving the receiver a characteristic in which its impedance to the desired band of wave length is very low in comparison with its impedance to the wave length above and below this band.

The curve in figure 1 shows the relation of admittance to wave length in a simple oscillating circuit which has the constants of the antenna ordinarily used and which is tuned to a definite wave length by the addition of a variable inductance.

An examination of this curve shows that, altho the maximum signal is obtained for the wave length to which the circuit is tuned, appreciable response is given to wave lengths differing considerably from those for which it is in resonance.

*Received by the Editor, September 24, 1922. Presented before The Institute of Radio Engineers, New York, October 4th, 1922.

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In order to obtain the desired selectivity, it is necessary considerably to increase the time constant of this circuit. This result can be accomplished in one or both of two ways: namely, by increasing the inductance element with a corresponding reduction, of capacity or by decreasing the effective resistance by regeneration.

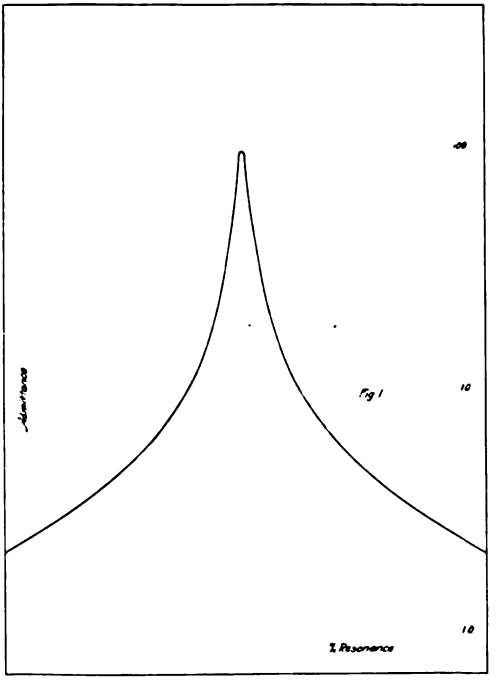

FIGURE 1

The curve in Figure 2 shows the effect of placing an additional capacity of 25 micro-microfarads in series with the circuit with a corresponding increase in inductance to bring the circuit in resonance with the same wave length as under the first condition. It will be noted that the selectivity is very considerably improved.

In the case of a vacuum tube detector, which is nominally a voltage-operated device, the large inductance implies a correspondingly large voltage available for operation of the detector, with the resultant increase in signal strength. In the case of the crystal detector, the maximum signal strength is obtained when the effective resistance due to the detector is equal to that of the balance of the antenna circuit. It therefore should be connected

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across such part of the inductance as will give the best compromise between selectivity and sensitivity.

The use of the regenerative vacuum tube offers the further possibility of increase of selectivity with the additional advantage of a very marked increase in sensitivity.

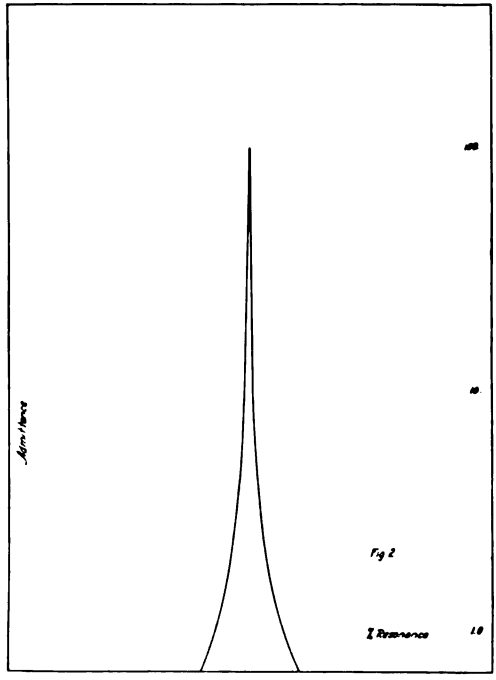

FIGURE 2

The curve, Figure 3, shows the relation of admittance to wave length of the same circuit as that for Curve 2, with the exception that the resistance element is assumed to be one percent of that in Figure 2. This is an amount of regeneration which can readily be obtained. The ordinates of this curve are drawn to a scale one hundred times that of Figure 1 and 2, and it might be assumed that the signal strength would be one hundred times that which would be obtained from the circuit of Figure 2. This condition does not necessarily follow, owing to the fact that there is a definite limit to the component of antenna current which is proportional to the incoming signal.

This condition may be illustrated by the diagram, Figure 4. In this diagram, *O E* represents the incoming signal field affecting

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the receiving antenna. Should the impedance of the receiving antenna circuit be infinite, the voltage induced in this circuit will be in the phase $O\,C$. For finite values of resistance impedance in this circuit, the current will be bounded by the circle $O\,B\,A$. Thus, for a given value of resistance impedance, the current will be represented by the line $O\,B$. The field surround-

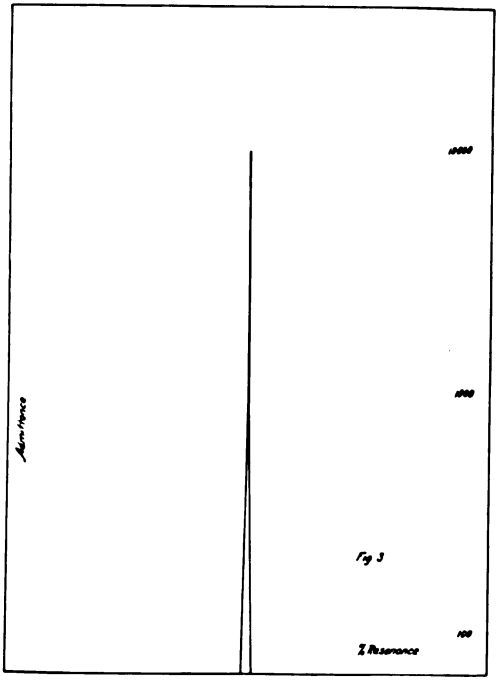

FIGURE 3

ing the antenna due to this current will have the same phase and relative length, and the total effective field will be the sum of $O\,E$ and $O\,B$, or $O\,D$. For zero resistance the current will have the phase and relative length $O\,A$, with a zero resultant field. Further consideration will show that this ultimate received antenna current is independent of the height of the antenna, provided all sections of its length are affected by the same field intensity, it being dependent only upon the field per unit length.

The antenna therefore may be considered as a constant voltage generator, having a definite internal impedance, which is proportional to antenna height. This generator supplies a load circuit having the constants of the oscillating circuit.

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In the case of a regenerative system in which the regeneration is carried out to such an extent as to produce oscillations, the current due to the incoming signal will be super-imposed on the local current, and have a value dependent entirely upon the effective resistance but independent of any local oscillating current.

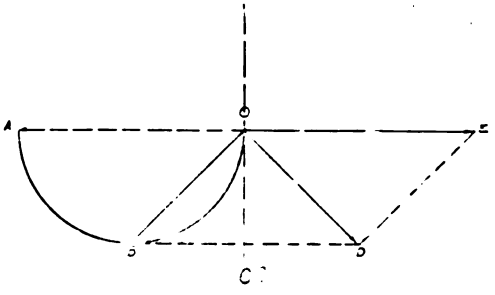

FIGURE 4

Figure 5 shows the conditions determining the resistance of the antenna circuit under the oscillating condition. In this curve the line G shows the relation of voltage impressed on grid terminals to the oscillating component of plate circuit. Curve P shows the oscillating component of plate circuit set up by this impressed grid voltage. From this curve it will be seen that, once the oscillations are started, they will increase to a point where the curve P intersects the line G. The effective resistance of the antenna circuit is determined by the relation of the angle of this intersection to the angle of G with the base. In actual practice, it is possible to reduce the angle of intersection at this point to such a value that the antenna current due to incoming signal will closely approach the ultimate value. Any possible increase of the sensitivity is therefore limited to an increase of the inductance across which the detecting circuit is connected. The extent to which this increase can be carried out is largely a matter of design.

The limitation of sensitivity due to ultimate antenna current also imposes an apparent reduction in selectivity and is a feature which usually is not considered in the discussion of the oscillating circuit.

Referring to the curves, Figures 2 and 3, these show the characteristic of simple circuits made up of capacity, inductance

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and resistance. In the case of an actual antenna circuit, it has been shown that there is, in addition, a limiting impedance which is proportional to the height. In the consideration of the sharpness of tuning of the antenna circuit, it is necessary to consider this limiting impedance in addition to the actual impedance of the oscillating circuit. Therefore, the actual increase of sharpness of tuning which can be obtained by regeneration is largely determined by this limiting impedance, or, in other words, by the antenna height.

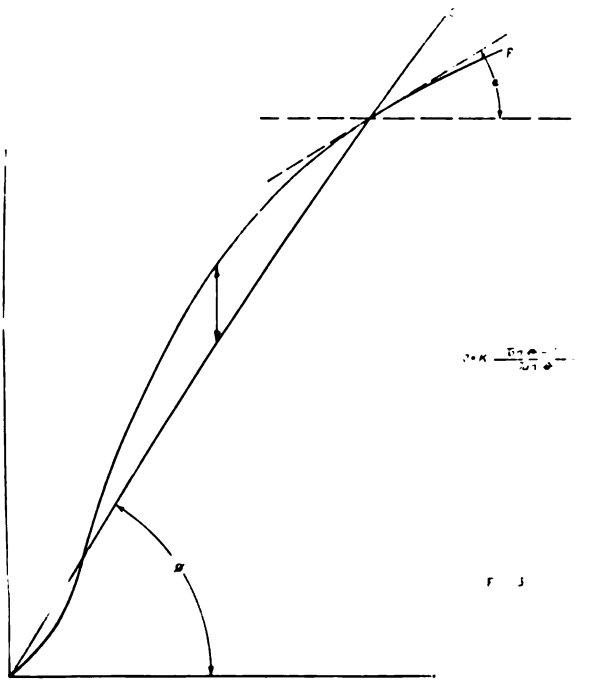

FIGURE 5

In Figure 6 are shown two curves taken with similar receiving sets, but on antennas of different heights. The left-hand curve is from a single-wire, inverted-L antenna, having a height of 35 feet (10.6 m.) above ground, and a length of horizontal portion of 75 feet (23 m.). The right-hand curve was taken from an antenna having a height above ground of 15 feet (4.6 m.), the length of horizontal portion being the same. The same receiver was used in each case.

These two curves show the very great increase of selectivity to be obtained by the use of the low antenna. In fact, the in-

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crease is considerably greater than would be expected from consideration of the comparative heights of the two antennas. It is probably accounted for by the condition that the effective height of the lower antenna is a considerably smaller percentage of its actual height than in the case of the higher antenna, owing to the indefinite height of the ground connection which was made to the hot water heating system, thus giving an effect equivalent to raising the height of the actual ground.

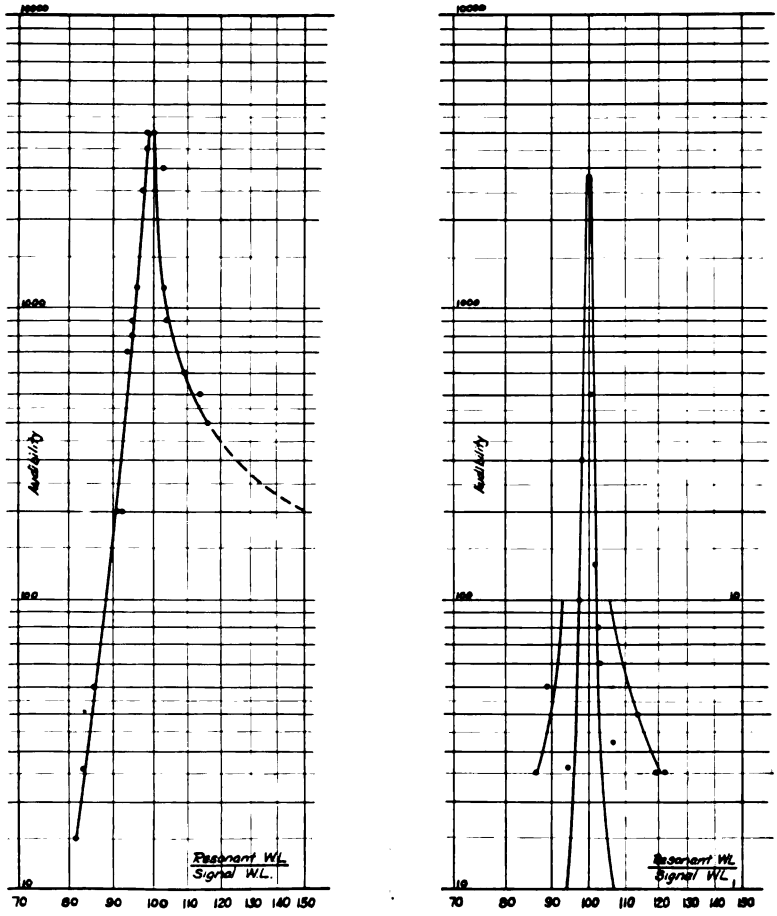

FIGURE 6

Due to the absorption by objects on or near the ground, it is usually impossible to realize completely the condition of equal signal strength with low as with high antenna, and of course the

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possibilities in this direction depend on the surroundings of the antenna in question.

Under conditions in which the reduction of signal strength with height is due, as is often the case in thickly built-up districts, to the appreciable absorption near the ground, it is possible to improve the selectivity of the antenna by the use of a coupled secondary circuit in the receiving set. If another resonance circuit of the same constants were connected to the output circuit of a vacuum tube amplifier connected to a resonance circuit having the constants corresponding to that of Figure 2, the characteristic of this double circuit would be proportional to the product of the characteristic curves, which, it is evident, would give a very greatly increased selectivity.

This arrangement constitutes the ideal method of improving the selectivity of a receiver. If, in place of the relay coupling between the oscillating circuits, a direct coupling were used, the relation of the secondary to primary would, in a sense, be a duplicate of that existing between primary and the transmitter, with the equivalent antenna height of secondary corresponding to the looseness of coupling, thus permitting the possibility of a receiver connected to a high antenna and with the selectivity of a low one. However, the extent to which this can be carried out is limited by the fact that, as the apparent secondary antenna height is reduced by reduction of coupling, the reduction of primary resistance by regeneration is also reduced, with a corresponding limitation of ultimate secondary signal current and its attendant reduction of selectivity.

Owing to the difficulty of carrying out the necessary interacting adjustments, the use of a coupled circuit receiver is justified only under those particular conditions in which it is not possible to take advantage of the selectivity of the low antenna.

A further possibility towards the solution of the receiver problem for congested districts is the use of a closed coil or loop in place of an open antenna. The loop receiver will have the advantage that, similar to the short antenna, it embraces a limited field area, and at the same time can usually be placed sufficiently above ground level to be in a somewhat denser field than would be the case with a corresponding short, open antenna. The limiting impedance of the loop is comparatively low, but as the induced signal voltages are also low, it is necessary that a regenerative system be used in order to obtain the benefit of selectivity. It, of course, has certain possibilities of eliminating interference, due to its directional properties. In general, the

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loop receiver under its best conditions, will give results which are practically identical with those obtained from a receiver connected to a properly proportioned, open antenna, barring, of course, the possibility that the relative position of the interfering station may be such as to permit of advantage being taken of the directional effect. It has the advantage of convenience of installation and of not being restricted to location as regards height where the field density may be low. However, the first cost and maintenance expense of such a receiver are far greater than those of the equivalent regenerative set on an open antenna, and for these reasons, cannot, at the present time, be considered as a real competitor of the open antenna receiver.

The foregoing conclusions in regard to the conditions effecting selectivity are based on the premises that the receiver is used for the reception of modulated continuous wave signals and that the interferences to be dealt with are those set up by similar transmitters.

In the case of interference resulting from atmospherics, or static, the particular precautions which would minimize interference from other transmitters would have insignificant effect, and at the present time there is no practical scheme which gives any appreciable reduction of interference from static.

In the case of interference from damped wave transmitters, the effects will lie between the conditions of a modulated continuous wave signal and static, the similarity to one or the other being determined by the decrement of the interfering signal.

In the case of the usual amateur spark transmitter, which is the one most likely to set up the interference, the conditions will be not far removed from those governing the effects of static, owing to the usual high decrement of these transmitters.

The solution of the problem of interference from this source should be in the direction of elimination of the spark transmitter by the substitution of continuous wave sets, rather than by any receiver development, owing to the actual great width of wave band covered by even the best type of spark transmitter.

The one serious defect of the regenerative receiver is the interference it can produce on other receivers due to radiation when regeneration is carried to the oscillating point. The intensity of this radiation can be controlled to a certain extent by the antenna circuit constants and the constancy of regeneration of the receiving set with various wave length adjustments.

With increase of the inductance element in the antenna circuit, the antenna current for a given voltage applied to a receiving

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tube is correspondingly reduced, with attendant reduction of interference; and, with constancy of regeneration with varying wave length adjustment, the possibility of the set producing strong oscillations during the tuning operation will be reduced. This latter feature has considerable bearing on the system of regeneration which it is advisable to employ.

The mechanism of regeneration implies a coupling between anode circuit of tube and oscillating circuit, such that any fluctuations in anode current sets up corresponding oscillations in the oscillating circuit, and of such phase relation as to reinforce the original oscillations which had acted on the grid of the tube. This coupling may be electro-magnatic or electro-static.

In the electro-magnetic coupling a coil which is in series with the anode circuit is so disposed that its field embraces more or less of the inductance in the oscillating circuit.

With the electro-static coupling, advantage is usually taken of the capacity between grid and anode elements of the tube and its connections. When the impedance of the anode circuit ia altered by a varying grid potential, corresponding potentials are induced on the grid element thru the capacity of tube and connections. When the grid is connected to a resonant circuit and the impedance in the anode circuit is principally a resistance, the phase relation of induced potential on grid thru anode is 90 degrees displaced from the original controlling potential of the grid. An inductive reactance in the anode circuit so shifts the induced potentials that it assists or adds to the grid controlling potential. A capacitive reactance so shifts the phase relation that the induced charge on the grid subtracts from the original controlling potential. Therefore, by incorporating a variable inductance in the anode circuit, the amount of regeneration can be controlled at will.

The inductive coupling method of regeneration possesses the advantage that when the anode coil is coupled to the variable inductance which controls the wave length of the oscillating circuit, the amount of regeneration remains practically constant over an extended wave length band. In the case of the capacitive coupling, both the effect of capacity between anode and grid circuits and the effect of inductance in the plate circuit vary with change of wave length. The regeneration, therefore, requires readjustment with each readjustment of wave length of the set. For this reason the operation of tuning-in a signal is more complicated. The inductive coupling method, however, requires proper proportioning of the relation between coupling

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coil and tuning inductance, while the capacitive coupling merely requires the insertion of a variable inductance in the anode circuit and the necessary by-pass condensers to shunt the radio frequency fluctuations in this circuit around inter-tube transformers or telephone receivers. For this reason, this arrangement has been a great favorite with radio experimenters as well as manufacturers of receiving apparatus, who have merely assembled conventional parts in a containing case.

From the standpoint of interference produced by the receiver, therefore, the inductive coupling method is considerably superior to the capacitive coupling, owing to the fact that the coupling can be set at some value below the oscillating condition, which it will maintain thruout the whole range of wave length adjustment. The degree of regeneration which can be obtained over the whole range without oscillations occurring at any point is, of course, dependent upon the excellence of design of the set. In case of the capacitive coupling, as the degree of regeneration increases at a very rapid rate with decrease of wave length setting, it is necessary, in order to obtain any appreciable regenerative effect, that simultaneous adjustment of anode inductance be made with adjustment of wave length.

The design of the oscillating circuit tuning elements of a receiver is largely determined by the range of wave length desired and in the regenerative scheme employed, if any. The inductance or capacity elements alone may be variable, or, to obtain a greater range of wave length adjustment, they may both be variable.

When the inductive coupling for regeneration is employed, it is usually desirable that at least the inductance element in the oscillating circuit be varied for adjustment of resonant wave length, as by this means the proper coupling between the resonant circuit inductance and the feed-back coupling coil for constant regeneration at various wave lengths can be obtained.

In Figure 7 is shown the interior of a typical regenerative receiver, using inductive coupling for regeneration, and simultaneous variation of both inductance and capacity for wave length adjustment. This receiver covers a comparatively long range of wave length with one continuous adjustment, and in order to compensate for the comparatively small angle of adjusting of the knob which will carry a heterodyne note thru the audibility range, it is fitted with a so-called "vernier" condenser, consisting of a small single plate variable condenser in parallel with the

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main tuning condenser. The total range of this condenser is made equivalent in wave length change to a few divisions of the main tuning dial. This receiver is normally intended to be used as a single circuit set. However, for conditions surrounding the antenna under which it is not possible to realize the necessary selectivity, it can be used as a tuned coupled circuit set by using a separate primary tuner, as shown in Figure 8 the secondary tuner being merely short circuited on itself.

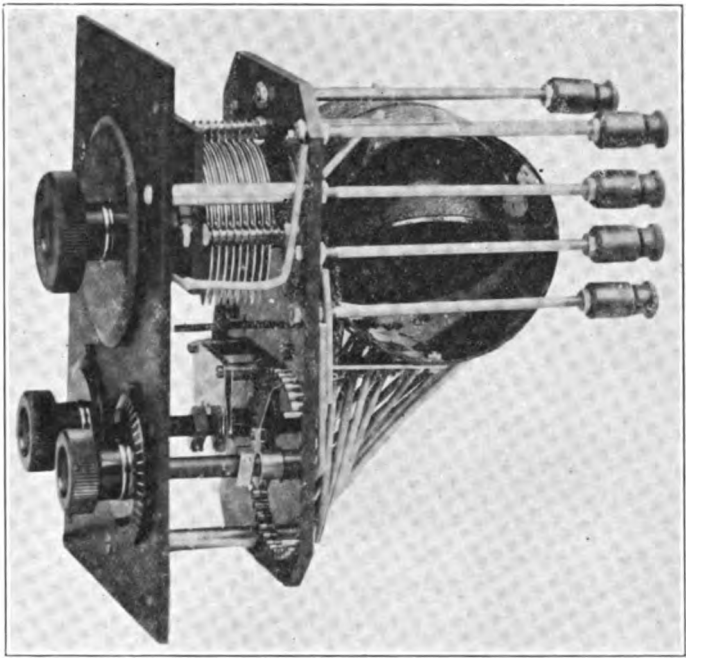

FIGURE 7

When the boxes containing the two elements are placed side by side, they give about the proper coupling for usual operating conditions. As the coupling is between the variable inductances, these can be proportioned so that they maintain the proper coupling value over the whole range.

In Figure 9 is shown a single-circuit regenerative receiver in which the inductance element alone is varied for the purposes of tuning, a fixed capacity being used in series with the antenna circuit for the purpose of increasing the selectivity. However, this fixed capacity is made in two steps, thus permitting two separate wave length ranges. The regenerative coupling coil

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and the main tuning inductance are so inter-related as to give practically constant regeneration over the whole range of possible wave length adjustment, when the set is connected to the average antenna.

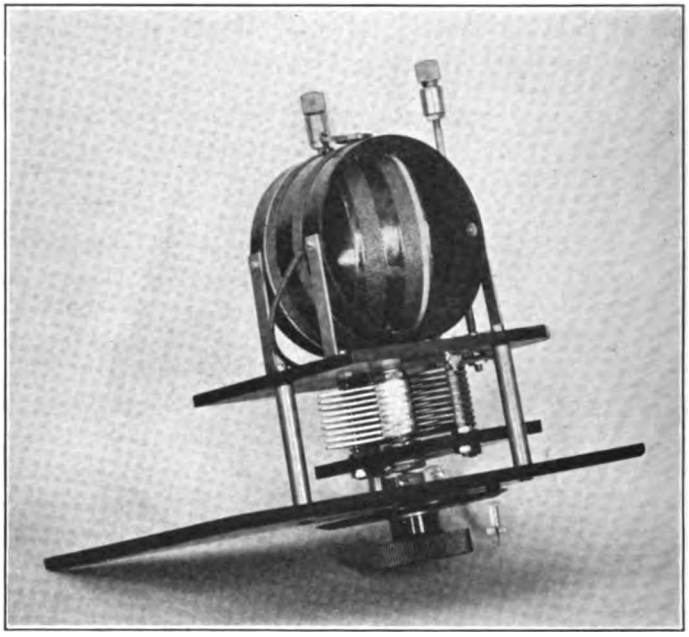

FIGURE 8

The foregoing remarks mainly cover questions of design affecting the tuning elements of the receiver, and on the general assumption that a three-element vacuum tube receiving system of the requisite sensitivity is employed.

The problems which may be presented for future development will be influenced largely by the condition imposed on the operation of the transmitting stations. With the transmitters grouped in one band of wave length, the possibilities of improvement are very remote. With the separation of transmitting waves, the ease of solution of the interference problem increases with the extent of this separation. The logical solution would appear to be a separation which would correspond to the possibilities of available receiving apparatus, and it is probable that, as the number of transmitters continues to increase, with a corresponding reduction of wave separation, the development of

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receiving apparatus will keep pace with the increasing exactitude of requirements.

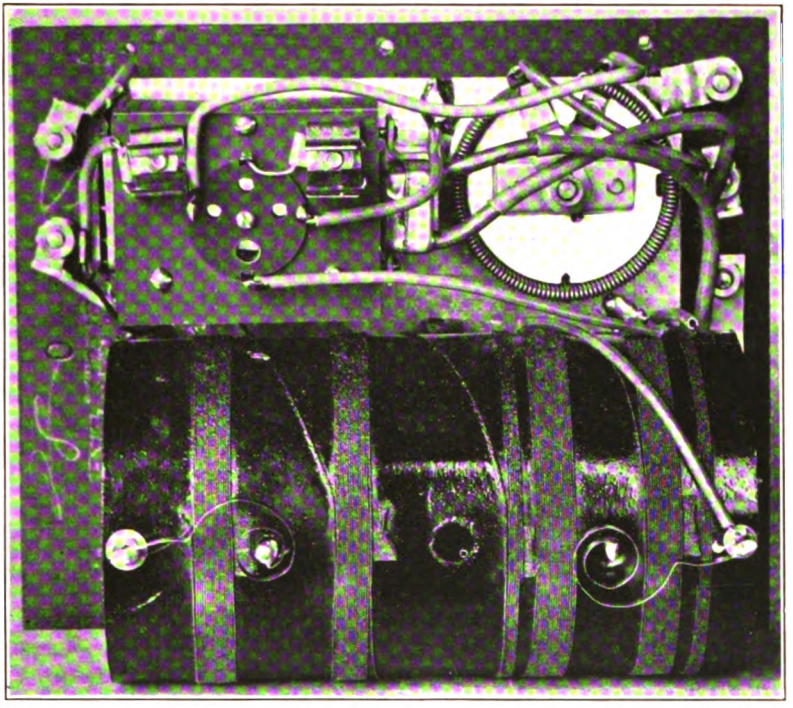

FIGURE 9

SUMMARY: The requirements and possibilities of a receiver for radio-telephone broadcast signals and the importance of considering the antenna in the design of this receiver are discussed. It is brought out that the increase of signal strength which is obtainable by regeneration is limited to a definite value, which is determined by the strength of the incoming field, and it is shown by curves that this maximum signal strength is independent of antenna height. Some of the possibilities in the direction of eliminating interference by various circuit arrangements are discussed.

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OSCILLOGRAPHIC STUDY OF ELECTRON TUBE CHARACTERISTICS*

By

E. Leon Chaffee

(Harvard University, Cambridge, Massachusetts)

The following paper describes an oscillographic method of studying vacuum tubes which was developed for use in an investigation on electron tube detectors containing gas. The method is, however, applicable to the study of any three-electrode tube and there are appended to the description of the apparatus curves taken on several types of vacuum tubes.

The point-by-point method of obtaining the static characteristics of a vacuum tube is both laborious and inaccurate. So much time is required to make the large number of readings necessary to obtain even one curve that conditions are likely to change during the process. This is particularly true in the study of gas-filled tubes. Furthermore, small kinks or points of irregularity in the characteristic curves, sometimes of great importance in explaining the action of gas-filled detectors, can only be investigated by some oscillographic method such as is here described.

The apparatus may be used, in addition to giving the static characteristics, to show the operation of a tube as a detector or amplifier by oscillographing the changes in plate and grid currents as small potential variations are impressed on the grid. The results obtained in this way are of pedagogical value in showing the action of amplifiers and detectors.

A brief description of the apparatus and method follows. The deflections of two vibrators of a special oscillograph are recorded photographically on bromide paper wound on a revolving drum. Except in a special use, one vibrator records the plate current and the other the grid current. A motor rotates the drum and at the same time slides a contact over a circular potentiometer so that distances around the drum, which is a direction lengthwise of the bromide paper, are proportional to volts.

* Received by the Editor, March 8, 1922.

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Figure 1 shows the connections used in obtaining the curves of plate-current against grid-volts for any constant value of the plate volts, E_b. The potentiometer referred to above is shown

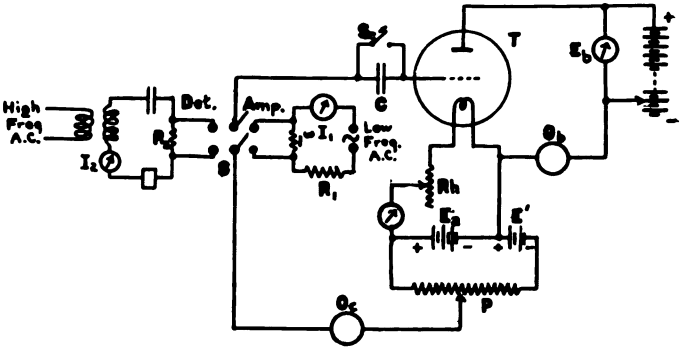

FIGURE 1

at P, and in this case is connected across the filament battery E_a and the extra battery E' so that the potential of the grid is made to vary from $-E'$ to $+E_a$ with respect to the negative end of the filament. The plate vibrator is shown at O_b and the grid vibrator at O_c. In the grid circuit is a condenser C which can be shorted by switch S_c. A switch S is also included in the grid circuit. When S is thrown to the right, a 1-ohm resistance thru which flows a small measured alternating current of about 6 cycles, is connected in the grid circuit. By this means a small slow variation of potential is superposed on the gradually increasing potential caused by the movement of the contact over the potentiometer P. The plate current shows a corresponding small alternate increase and decrease due to the small superposed alternating potential in the grid, the amplitude of the plate current variation being a maximum on that part of the characteristic curve where the amplification is a maximum.

When switch S is thrown to the left, the tube is operated as a detector. A small resistance R_2 thru which a small measured radio frequency current flows is included in the grid circuit. An interrupter B periodically interrupts this radio frequency current at the rate of about 6 times per second. Each time the radio frequency potential variations are impressed on the grid, the plate current shows a change if rectification takes place and the change in plate current is a measure of the amount of rectification, or sensitiveness of the tube as a detector.

Curves giving the variation of plate current with plate vol-

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tage for various constant values of grid voltage are of well known interest in studying the characteristics of electron tubes. Figure 2 shows the connections for taking curves of this type. P is the motor-driven potentiometer which now varies the plate potential from zero upward as the drum carrying the bromide paper rotates. P' is a second potentiometer substituted for P in Figure 1 and used to set the grid voltage to any constant value. Otherwise the connections are the same in the two arrangements of Figures 1 and 2.

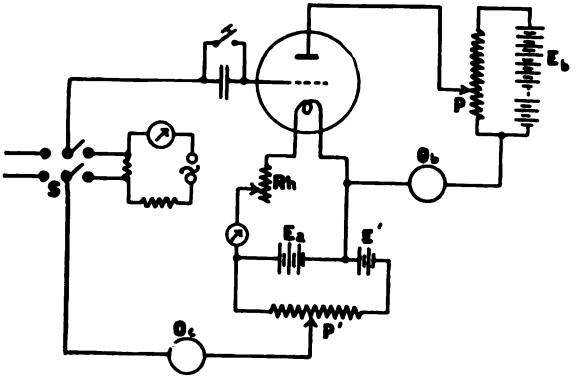

FIGURE 2

When a tube is used as a detector only, a strong signal impressed on the grid will give an appreciable fractional change in plate current. The effect of a weak signal may be studied by a special method of magnification explained by the connections shown in Figure 3.

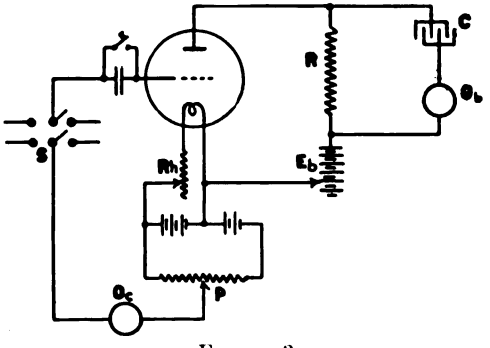

FIGURE 3

About the high resistance R is shunted a large condenser C in series with the plate vibrator O_b. Placed in this position the

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vibrator carries no direct current, and deflects only when there is a variation in plate current. This arrangement permits the vibrator to be used at its maximum sensicivity, that is unshunted. When the plate current suddenly drops, the voltage across the resistance R drops and the large condenser C partially discharges thru the vibrator, giving a quick throw—the amplitude of which is roughly proportional to the magnitude of change of the plate current. The condenser C had, in the arrangement used, a capacity of 10 μf. and the resistance R was from 1,000 to 10,000 ohms, according to conditions. It is desirable to make R as small as possible consistent with sensitivity because a very high resistance in the plate circuit flattens the characteristics of the tube.

In addition to the connections shown in Figures 1, 2, and 3, means were provided for rapidly calibrating the two vibrators by sending 0.1, 1.0, or 10 milliamperes thru the vibrator, according to the amount the vibrators were shunted to reduce sensitiveness. These deflections caused by the calibrating current are recorded photographically after each curve. The abscissa voltage scale was also recorded photographically, as will appear on the curves.

The oscillograph is a reconstructed Duddell oscillograph. In place of the strip vibrators, which had insufficient sensitivity, two small d'Arsonval coils were substituted. Each coil was wound with 100 turns of one and one-half mil (0.0015 inch or 0.0038 cm.) wire on an ivory bobbin about $\frac{3}{4}$ inch (1.9 cm.) long

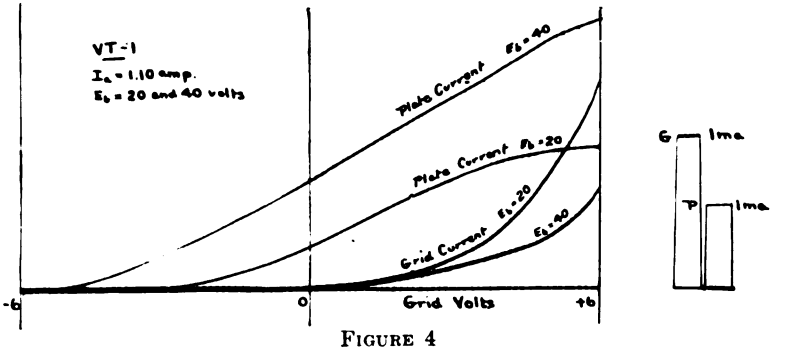

FIGURE 4

and $\frac{1}{8}$ inch (0.32 cm.) wide. These coils were held by taut suspension between the poles of the electromagnet. Over the active winding were wound a few short circuited turns to provide damping. The coils so constructed had a period of about 1/30 second,

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and a sensitivity of about 1 millimeter deflection at a distance of 1 meter (39.4 inches) for a current of 2 microamperes.

Figure 4 shows the usual static characteristic of plate and grid currents plotted against grid voltage for a Western Electric "VT-1" tube. The filament current and plate voltages are given on the curves. The calibration of the vibrators are given at the extreme right of the figure.

Figure 5 shows the plate and grid current plotted against plate voltage for the same tube. The grid current for grid voltage equal to zero is everywhere zero.

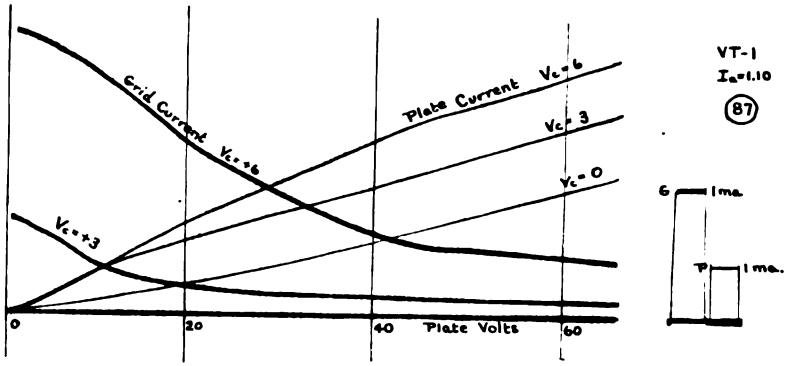

FIGURE 5

Figure 6 gives the plate and grid current plotted against grid voltage for a tube containing a trace of gas, probably air. The plate voltage was so high that the gas was ionized altho showing no perceptible blue glow. The positive ion grid current is evident

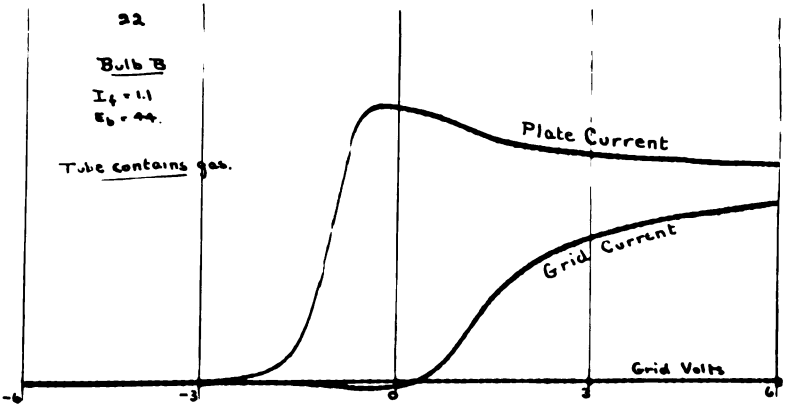

FIGURE 6

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between grid voltages of -1.5 and $+0.5$. Also the excessively steep rise of plate current should be noted giving a large mutual conductance which is characteristic of gas tubes.

Figure 7 shows characteristic curves of a gas tube taken similar to those of Figure 6, except that an alternating poten-

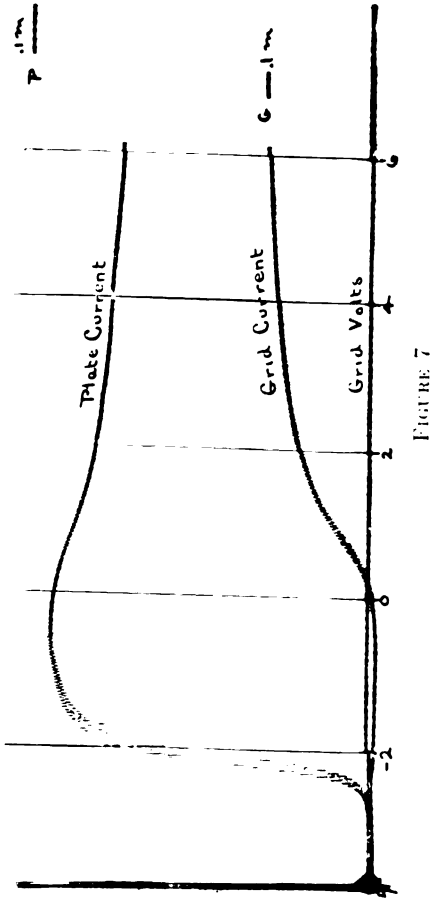

FIGURE 7

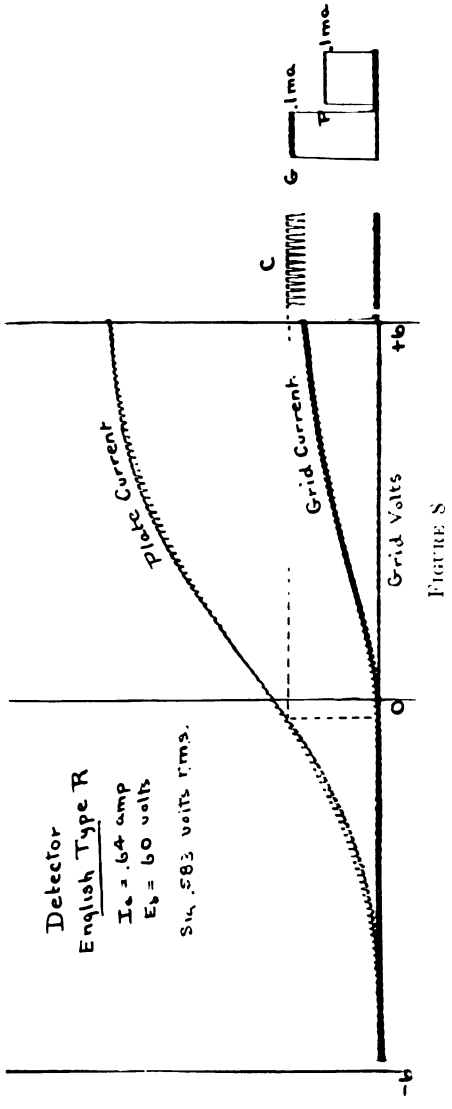

FIGURE 8

tial of 0.071 r.m.s. (root-mean-square) is impressed on the grid in addition to the slowly varying grid voltage for giving the

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abscissas of the curves. The amplifying effect of the tube is here shown.

Figure 8 shows an English Type "R" tube used as a detector. An interrupted radio frequency potential of 0.583 volts r.m.s. was impressed on the grid, and the resulting change in plate current gives an indication of the intensity of the signal and hence the sensitivity of the detector. The two regions on the plate current curve where rectification takes place is well shown. At the lower bend where $\frac{d^2 I_p}{dE_g^2}$ is positive, an increase in current results, but at the upper bend when the second derivative is negative, a decrease in plate current is obtained. The sensitivity with a grid condenser is shown at C at the right hand end of the curves. In this case, a decrease of plate current results, as would be expected, and the sensitivity in this case is greater than without a grid condenser.

Figures 9 and 10 show the detector action of gas tubes operating at high plate potential and low filament current. The trace of gas is perpetually ionized giving steep curves with sharp bends at the upper end where the detector sensitivity is great.

It is well known that a gas tube operated under certain critically adjusted plate and grid voltages and filament current often give phenomenal sensitivity as detectors. These sensitive spots on the characteristics are due to small kinks in the curves resulting from ionization of small traces of gas, too small in amount to make the tube break over into the familiar blue glow.

These kinks are exceedingly difficult to find when the characteristics are plotted point by point. It was to find these kinks that the apparatus described above was set up.

Figure 11 shows the detector action of a gas tube operating at a plate potential of 18 volts and rather high filament current. Under these conditions the kinks are enhanced. Two kinks are evident at a and b of the plate current curve but only the kink at b shows in the grid current.

The action at b is easily explained. Ionization of a small amount of some gas takes place, producing positive ions. These positive ions are attracted toward the grid but pass thru the grid toward the more negative filament. The space charge between filament and grid is partially neutralized, resulting in an increase in grid and plate current. The gas soon becomes totally ionized and no further increase in number of positive ions results. The curves then return to their former course.

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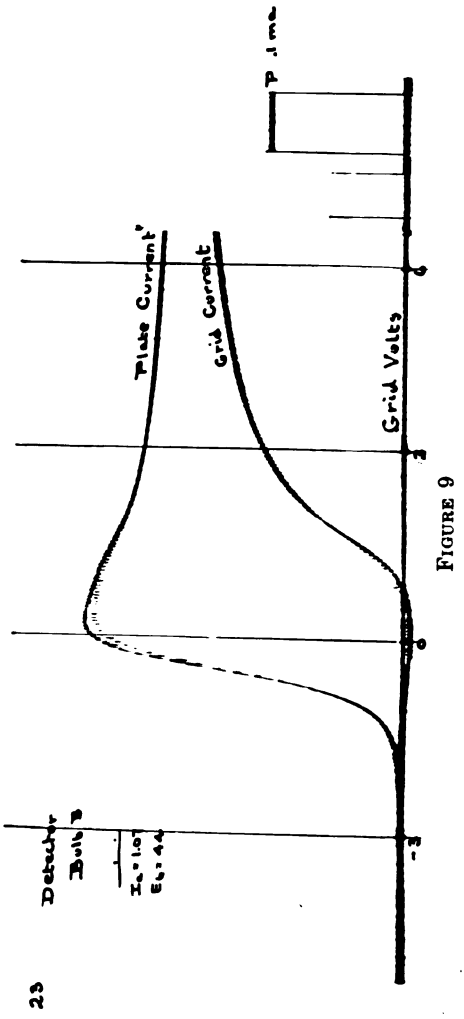

FIGURE 9

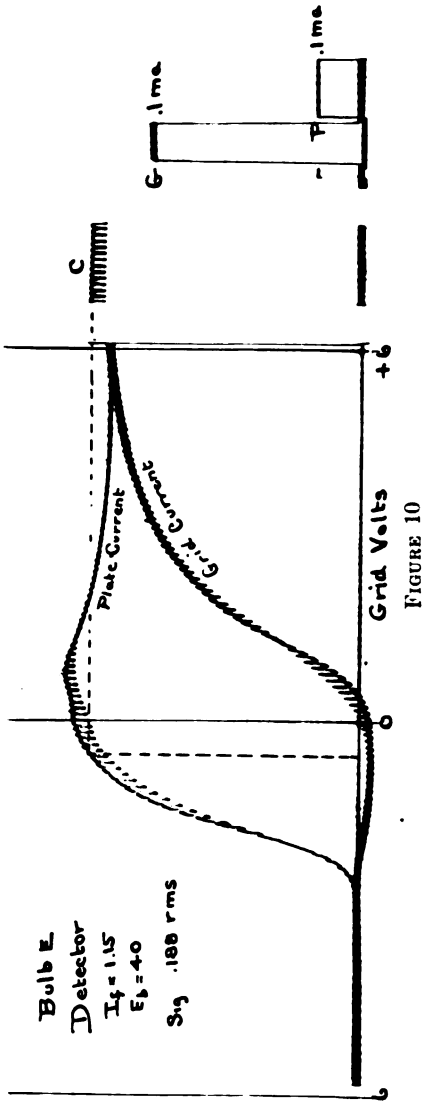

FIGURE 10

The effect at *a* is different, since any ionization would show in the grid current as at *b*. The electrons have an insufficient velocity to ionize the atoms of gas, but sufficient to excite them to radiate ultra violet light. At this so-called "resonance" velocity, some of the energy of the electrons is absorbed. The effective potential from plate to filament is thereby decreased, and a retardation or actual decrease in plate current results as the grid

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voltage is increased. The grid current is unaffected since the absorption of energy takes place between grid and plate.

The position of these kinks depends upon the kind of gas and the structural constants of the tube. Too much gas produces large changes of current which show hysteresis and do not give usable detectors.

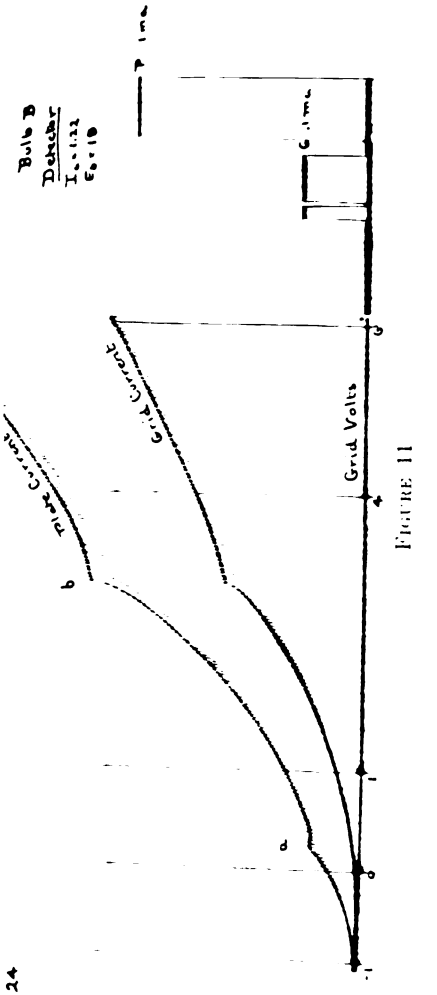

FIGURE 11

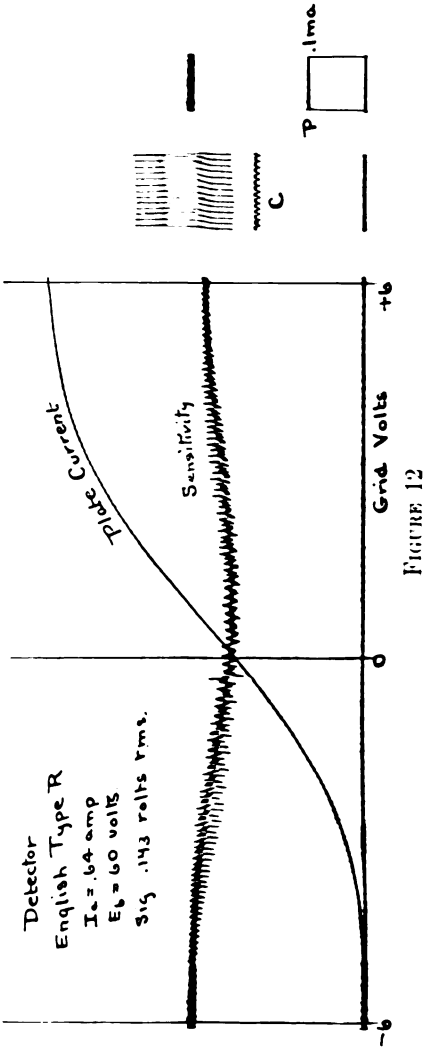

FIGURE 12

The signal voltages impressed on the grids of the detector tubes shown are of course excessive, and show sensitivity for a distance on either side of a kind equal to the extreme variation

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of grid voltage. In order to show more definitely the detector action at the kink, the signal voltage was much reduced and the variation in plate current magnified by the condenser connection shown in Figure 3 and described above. The grid vibrator was used to trace the magnified sensitivity.

Figure 12 shows the magnified sensitivity of a hard tube used as a detector. The extent of vibration indicates sensitivity. The changes in plate current are hardly perceptible on the plate current curve except when using a grid condenser as shown at C. Above the plate current line at C is the magnified sensitivity with a grid condenser.

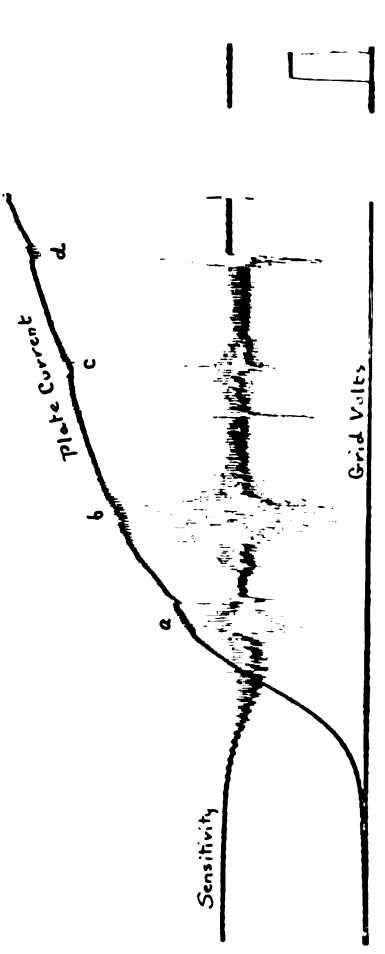

FIGURE 13

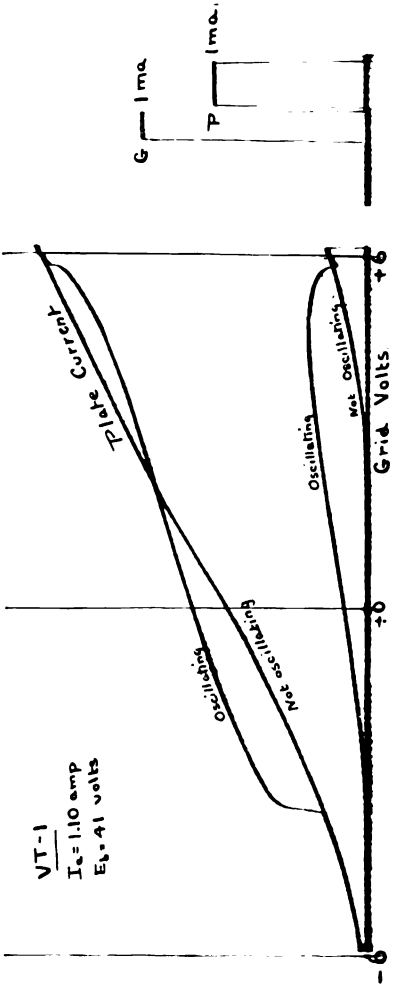

FIGURE 14

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Figure 13 shows the same method used for a gas tube. The plate current shows four regions of kinks. At *a* and *b* there are two close together, at *c* and *d* there is only one. The sensitivity is shown by the jagged curve marked "sensitivity."

Figure 14 shows the oscillating characteristics of a "VT-1" tube as the grid volts are varied. The curve is self-explanatory.

Cruft Laboratory,
Cambridge, Massachusetts.

SUMMARY: A special oscillograph is used to record simultaneously the plate current and the grid current of an electron tube. By superposing a slow audio frequency variation of voltage on the regularly increasing grid voltage during the photographing of the oscillogram, corresponding audio frequency variations are produced in the plate current, the amplitudes of which are proportional to the amplification of the tube at that setting.

Detector action can similarly be studied by applying a rising radio frequency voltage to the grid, and periodically interrupting it at a low audio frequency.

The study of tubes containing gas, and the recording of kinks in their characteristics is particularly facilitated by the use of the apparatus described.

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PHOTOELECTRIC ELECTRON TUBES*

By

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(Associate, Department of Electrical Engineering)

and

C. T. Knipp

(Professor of Experimental Electricity, Department of Physics)

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In recent years there has been put on the market, and used quite extensively, a class of vacuum tubes known as "gas content detectors." The advantage of this detector tube lies in the fact that it does not require a high plate voltage for operation, in fact the plate voltage is often as low as 18 volts; but must be adjusted carefully to the best value for loudest signal response. For such tubes the adjustment of filament current is also critical, and these two characteristics constitute a rather serious disadvantage. In the case of higher vacuum tubes used as detectors, adjustments are not so critical, the disadvantage being that higher plate voltages are necessary for good audibility of signal response.

During the year 1920-21 considerable work was done by the authors of this paper on the effect of the variation of pressure, and of the nature of gas content upon the efficiency, constants, and characteristics of detector tubes, and the results were abstracted in the March, 1922, issue of "The Physical Review." It was found that for a tube containing a certain gas the plate voltage for best signal response, which will be called the "operating voltage," decreased along a curve as the pressure increased, as shown in Figure 1. The curve shown was drawn from data obtained from three tubes, the gas content being air. For other gases the curves are similar in shape. Moreover it was found that for increasing pressures the operating voltage approaches the ionizing potential of the gas in the tube. Accordingly it should be possible to introduce into the tube a gas having a low ionizing potential, and thus obtain a detector having a corre-

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spondingly low operating plate voltage. The introduction of mercury vapor showed this to be a fact, altho in all cases the

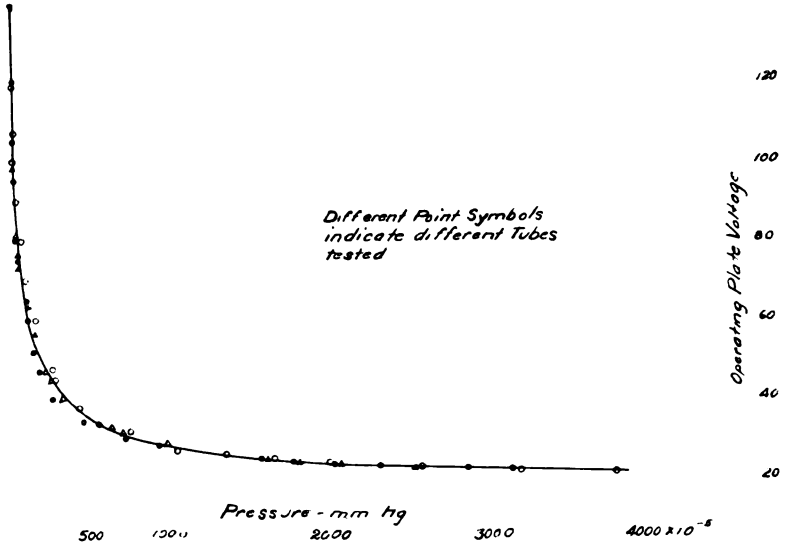

FIGURE 1

operating voltages were a few volts higher than the ionizing potential of the gas or metallic vapor content.

Recently this latter phase of the problem was again taken up, and three of the so-called alkali metals were introduced into detector tubes. The vapors of potassium-sodium alloy, rubidium, and caesium have ionizing potentials of less than four volts, and are the sensitive materials used to coat the walls of photo-electric cells. Small quantities of potassium-sodium alloy in a liquid state similar to mercury were put into several three-electrode tubes and the tubes were then tested and found to yield very remarkable results.

CHARACTERISTIC CURVES

Figure 2 shows plate current-grid voltage curves for various plate voltages. A peculiarity to be noted is the flattening out of the bend at saturation as the plate voltage increases. It should also be noticed that for negative grid voltages the curves are smooth, which is not the case for tubes containing gas, these latter having "humps" in their curves. Mercury vapor filled tubes also have the smooth curves mentioned. Figures 3, 4, and 5 show similar curves for different tubes. For all of the curves

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of this paper, the type UV-201 Radiotron was used. The tube of Figure 5 contained traces of gas so that the curve at 40 volts turned over much as it does in a gas-filled tube. This will be also noticed for higher plate voltages in the preceding three sets

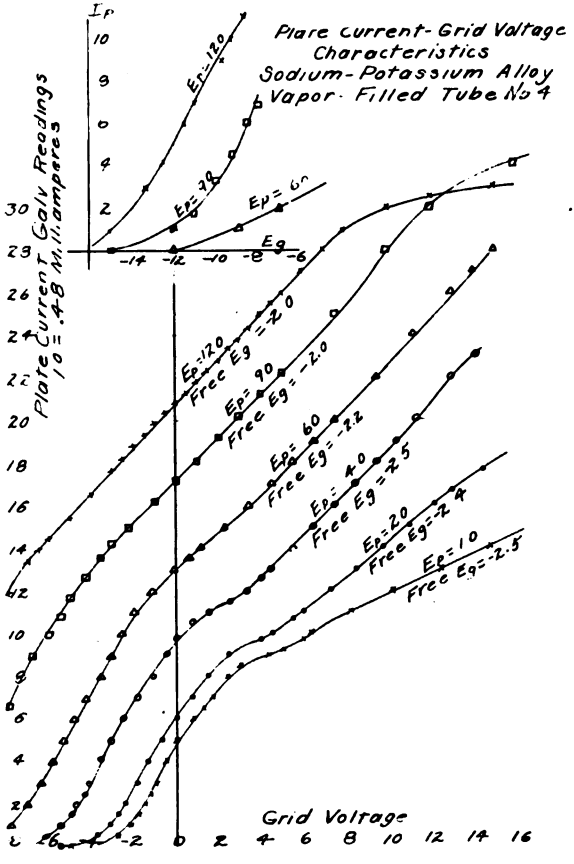

FIGURE 2

of curves. Below these "critical" plate voltages the curves again increase after passing the saturation point. In Figures 3, 4, and 5 it should be noted that the tube has quite a pronounced characteristic curve at zero plate voltage, when the plate was connected thru the galvanometer shunt to the negative end of the filament. In Figure 4 is also shown the zero plate voltage curve when the plate circuit connection is made to the positive end of the filament. The plate current is increased as would be expected. All curves were obtained for plate circuit connection

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to negative filament unless otherwise specified. With the connection to the negative filament lead, the plate current is at least fifty times as great as for a tube which does not contain the alkali metal vapor. This flow of current without any external

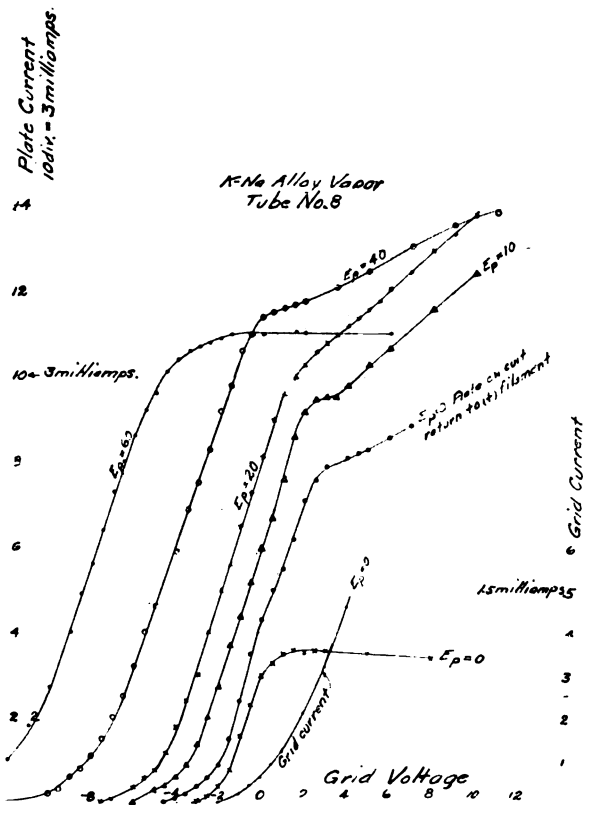

FIGURE 3

source of potential is also present in the photoelectric cell, hence the action of the tube as a detector of damped or undamped waves is wholly a photoelectric phenomenon controlled by grid potential at zero plate voltage, and partially so at other plate voltages. The negative free grid potential, as indicated on the curves by the plate current when the grid was disconnected, varied from -2 to -2.5 volts. Figure 6 shows characteristic curves for two alloy vapor tubes which were more completely exhausted before sealing off. Later curves will show detector and amplifier characteristics of these particular tubes. Figure 7 shows grid current curves for a typical tube, and Figure 8 shows a plate cur-

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rent-filament current curve. In Figure 7 the assymetry of the curve at -2 volts grid indicates that the tube is a sensitive detector.

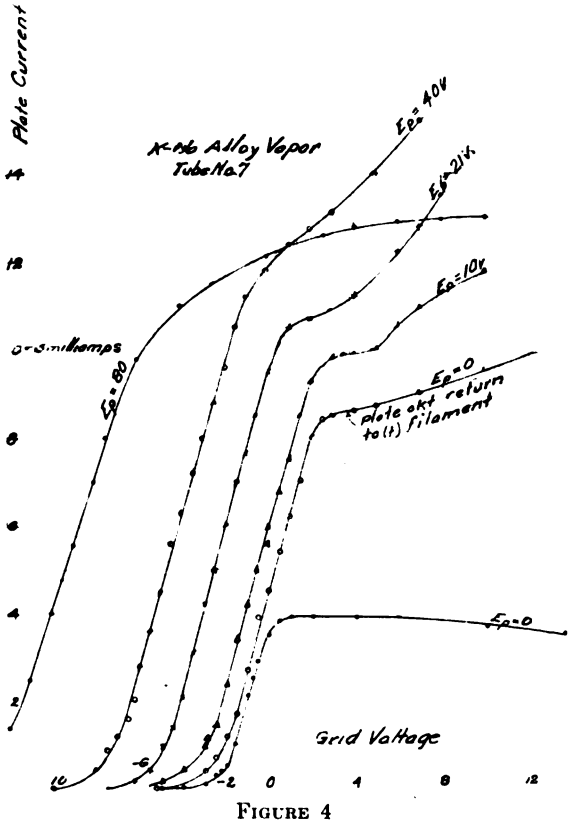

FIGURE 4

The shape of the plate current-grid voltage curves seemed to indicate that the tubes would function well as amplifiers since the curves are smooth and straight for negative grid voltages and it seems from their good performance as amplifiers, that the dynamic characteristics are also straight lines. Figure 9 shows plate voltage-grid voltage curves with constant plate current for two tubes. These curves are straight lines for high vacuum tubes, and, as the curves illustrated, show the alkali vapor filled tubes have this desirable characteristic. Curve A, Figure 9, is typical for a gas content tube, which is a very unsatisfactory amplifier as the slope of the curves, being the no load amplification constant of the tube, is not constant. The tubes

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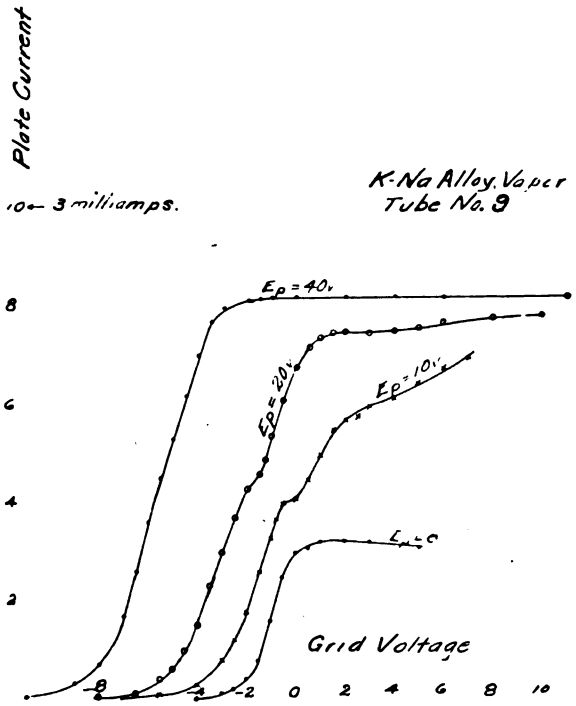

FIGURE 5

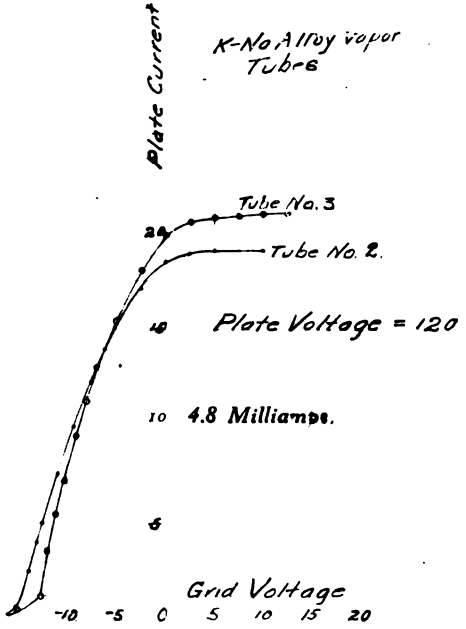

FIGURE 6

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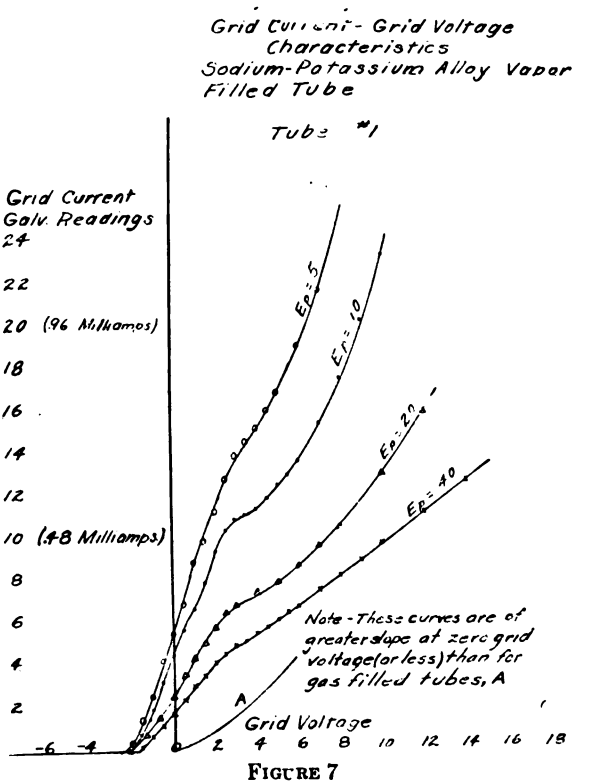

FIGURE 7

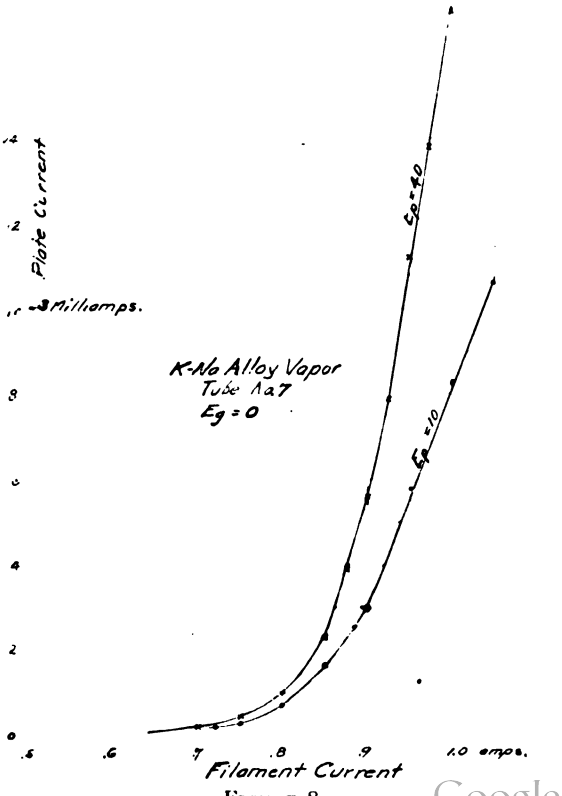

FIGURE 8

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of Figure 9 contained a small amount of the alloy so that the vapor pressure would be as high as possible. Figure 10 shows these same curves for a tube containing a small amount of the alloy evaporated into the tube and deposited on the tube walls

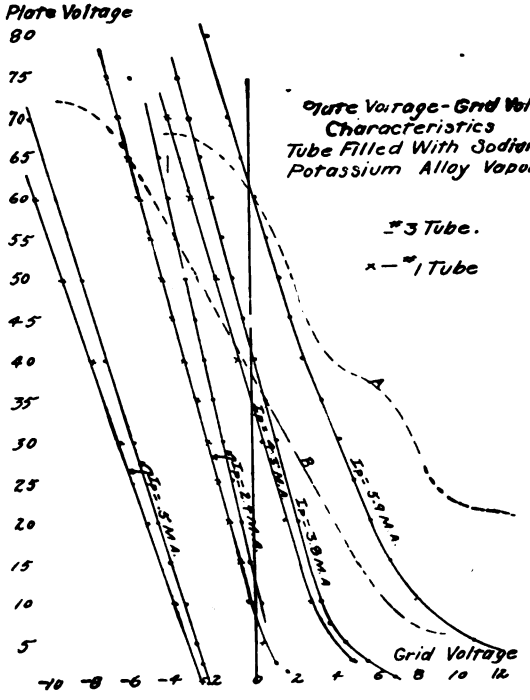

FIGURE 9

by condensation. The slope of the curves of Figures 9 and 10 indicate high amplification constants.

The amplification constants of three tubes were measured for different plate voltages and the curves of Figure 11 show the results. The method used for measuring the amplification constant, μ_o was that described in Van der Bijl's "The Thermionic Tube," page 203. The apparent increase of the value of μ_o at low plate voltages seems to indicate some source of error in the method, but precautions were taken to weaken the applied 1,000 cycle voltage, and to vary the grid potential with a grid battery. It is to be expected that the value of μ_o would remain constant for varying plate voltages for a high vacuum tube, but such a tube was tested and curve B obtained. In case of gas content tubes the value of μ_o does not remain constant but varies along

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a curve such as A in the figure. It is probable that the *effective* geometry of the tube is altered by the ionization of gas contained therein. The variation of mutual conductance, measured by a method described in the same reference, with plate voltage is

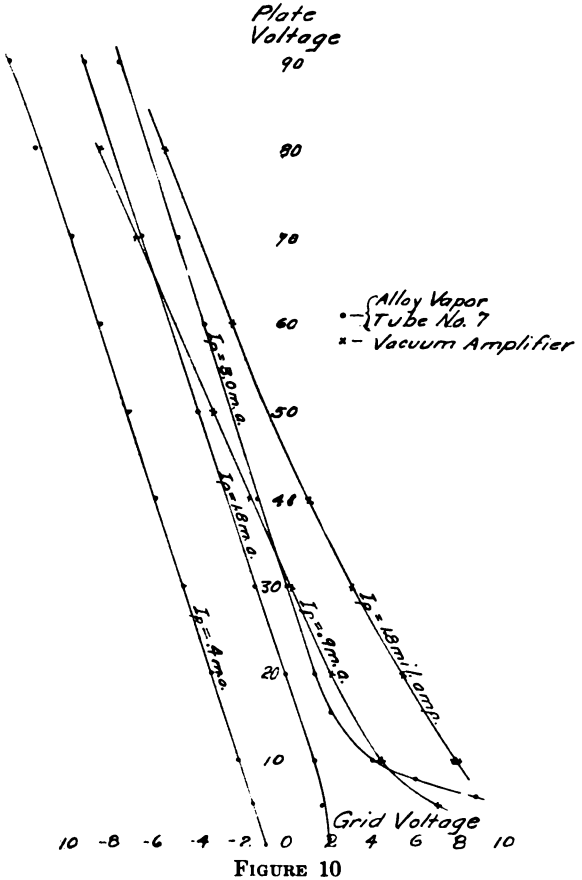

FIGURE 10

shown in Figure 12. These curves are interesting and indicate that the alkali vapor tubes would be excellent detectors in that the mutual conductance is high at low plate voltages, and is not extremely critical as regards adjustment of plate voltage. Curves A and B are typical of gas content tubes and fairly high vacuum tubes, respectively. For the alkali vapor tubes the mutual conductance increases gradually with filament temperature just as it does in the case of a high vacuum tube.

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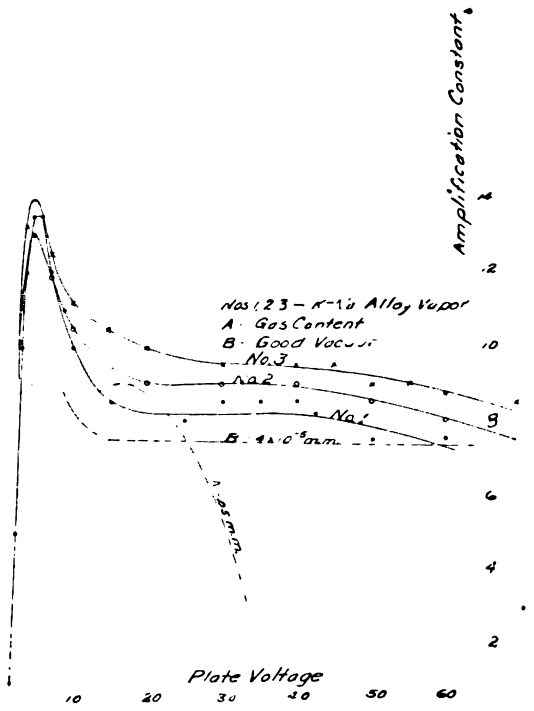

FIGURE 11

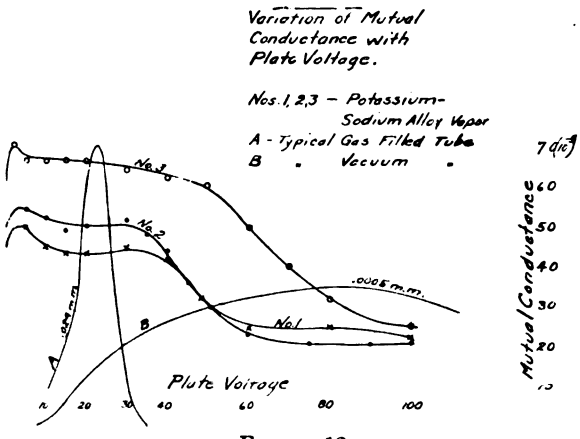

FIGURE 12

PRACTICAL OPERATION AS DETECTORS

To show how the tube functions as a detector of damped waves a comparison test circuit was connected as shown in Figure 13. A buzzer excited oscillating circuit is used together

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with a loop receiver, the inductances being 40 inch (1.02 m.) loops placed in adjacent rooms so that the buzzer could not be heard in the room. The intensity of response in the receiver was measured by matching it with a standard tone signal furnished by a 1,000 cycle audio oscillator and attenuated thru an audibility meter M. The proportion in which this signal is re-

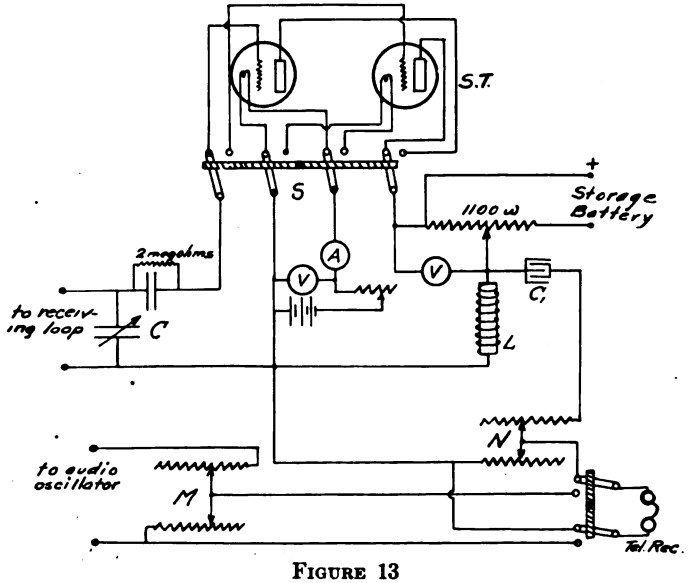

FIGURE 13

duced was calculated from the readings on the audibility meter setting. It was convenient to set the intensity of the received signal to a certain value by shifting switch S to the standard tube and measuring the audibility of the signal directly with audibility meter N. By means of the condenser C the received signal could be adjusted by detuning. A signal having a directly measured audibility of 5.5 times was used for all the measurements, as this represents a pretty weak signal. The purpose of the inductance L and condenser C_1 was to maintain constant plate potential on the tube when audibility meter N was varied. This method of measuring the efficiency of a detector is described in Van der Bijl's "The Thermionic Tube," pages 337 and 347, and is recommended by that author. Figure 14 shows how the per cent. intensity varies with plate voltage. It will be notde that while the maximum detecting efficiency occurs at about 10 volts the adjustment of plate voltage is not at all critical as is the case for a gas content tube. Moreover the intensity is quite

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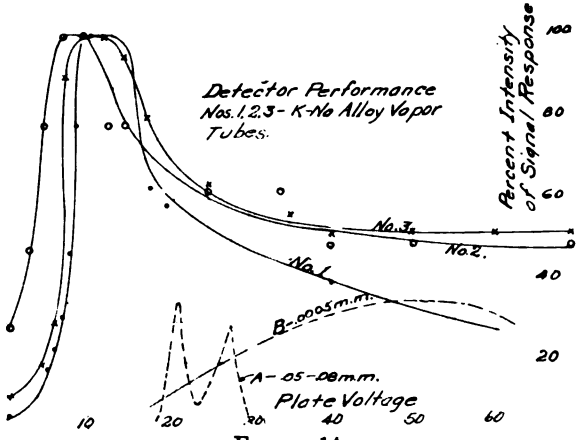

FIGURE 14

considerable at zero plate voltage and up to 50 or 60 volts. Curve A shows a typical curve for a tube containing a gas such as neon, nitrogen or argon at 0.05 mm. pressure. This shows the extremely critical nature of such a tube, and also the fact that the alkali metal vapor tubes are at least 3½ times as sensitive as the gas content tubes. A dozen tubes were filled and tested by comparing with several gas content tubes and it was found that the sensitiveness of the alkali vapor tubes was from 3 to 5 times that of the gas content tubes. Curve B is typical for the amplifier type tube, having a fairly good vacuum. By actual trial it was found that better results were obtained with a grid condenser of approximately 0.0003 microfarads and a grid leak of 2 megohms than with a carefully adjusted applied negative grid potential. It should be mentioned that it is important to use a rather weak signal when comparing detector tubes. If the received signal is extremely strong the intensity curve will be that of A, Figure 15, but if the intensity is weak the curve will be that of B, for a tube of fairly good vacuum. However, qualitative comparisons showed that the alkali vapor tubes were also most sensitive at 10 volts for strong signals of audibilities of 100-400 upon the standard tube; and that they also were much more sensitive than gas content tubes while receiving these strong signals. The variation of signal intensity with filament current was like that for high vacuum tubes, the intensity gradually increasing with filament current to a maximum and then gradually falling off with further increase.

The above tests and measurements, being quantitative were fairly conclusive proof that the potassium-sodium alloy vapor

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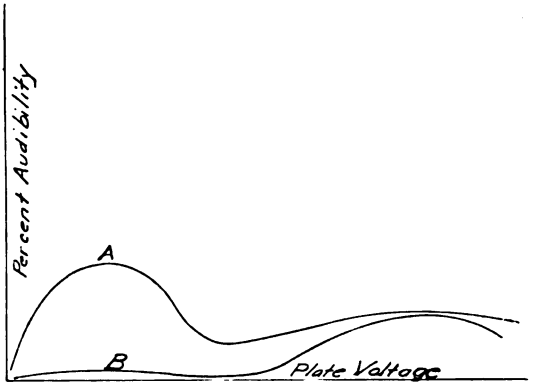

FIGURE 15

content detector tubes are far superior in every way to the common or inert gas content tubes. However, to be sure as to their practical utility the tubes were placed in standard receivers to receive the 2,500 meter spark station at Arlington, the 17,000 meter station at Annapolis, and the 360 meter broadcasting stations at Pittsburgh, Schenectady, Detroit, and Chicago. The results obtained were consistent with the measurements. The tubes were used as oscillating detectors for receiving the broadcasting stations by the regenerative and "zero beat" methods, and also by the heterodyne method to receive the 17,000 meter Annapolis Station; and the authors were astonished at the results. Speech and signal reception were remarkably clear and distinct, and with practically no need of frequent readjustments, as are often needed when using gas content detector tubes. The tubes even function fairly well as oscillating detectors at zero plate voltage, receiving all of the above mentioned stations, using an antenna 50 feet (15 m.) high and no amplifier.

They were also used as amplifiers in these same circuits, and gave louder and clearer speech with 10 volts on the plates than did vacuum amplifier tubes at 30 or 40 volts. In regard to the matter of the life of the filament this has not yet been determined, but some of these tubes have been used about 20 hours and no increase in filament resistance has been observed. It is known to chemists that potassium or sodium is capable of forming an alloy with tungsten, but no doubt the temperature of the filament keeps the vapor sufficiently free from its surface to prevent appreciable action. No deposit of the alkali metal remains upon the electrodes or the stem supporting them after the filament is once heated. In the process of preparing the tubes the fila-

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ment is maintained incandescent while distilling over the potassium-sodium alloy, and any deposit of the alloy upon the electrodes or supporting stem is prevented. Three of the tubes have been used intermittently for three months and no increase of filament resistance has been observed. The authors are of the opinion that the filament life of these tubes will be considerably better than that of the gas content tubes, especially since the sensitiveness is greater at a reduced filament temperature. In all of the foregoing tests the filament voltage was maintained constant at about 4.7 volts.

It is hoped that further investigation will show some other alkali metal vapor, or other vapor to be still more effective in three-element electron tubes. Also some particular proportions and dimensions will show maximum results. The potassium-sodium alloy was kindly furnished by Dr. Jakob Kunz.

Laboratory of Physics,
University of Illinois,
July 1, 1922.

SUMMARY: Three electrode tubes containing alkali vapor metals or vapor of alloys of alkali metals possessing low ionizing potentials and the characteristics of a photoelectric cell give remarkable results as detectors both in the plain and the oscillating condition with 10 volts on the plate, these detectors are extremely sensitive, at least three times that of the gas content tube. The photoelectric properties cause the tube to function fairly well with zero plate voltage. It is probable that the source of energy in this case is the luminous and non-luminous radiation from the incandescent filament. These tubes also make sensitive amplifiers.

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APPENDIX I*

PREPARATION OF TUBES—The potassium sodium alloy was contained in an evacuated glass tube A, in Figure 1. Two electron tubes, as shown in the figure, were connected to the *T* connection and rested in a horizontal position. Tube *B* led to the

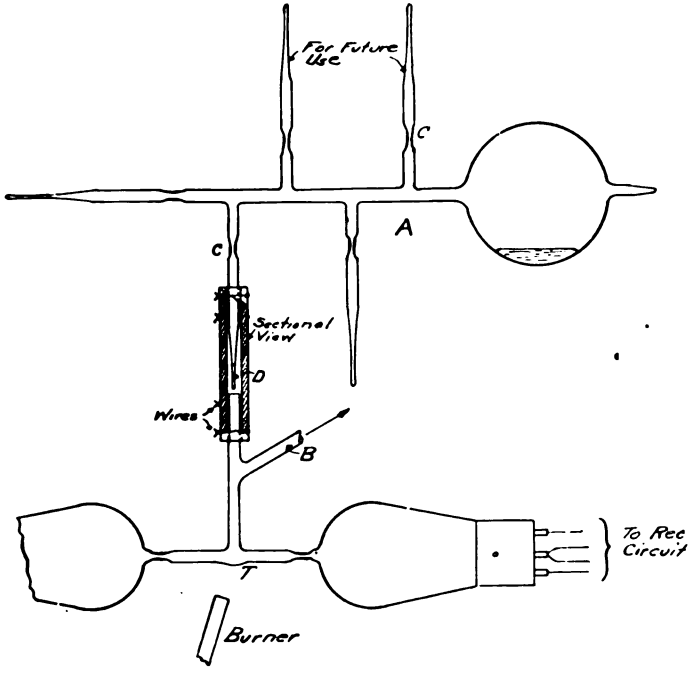

FIGURE 1

evacuating system consisting of charcoal tube immersed in liquid air, phosporous pentoxide tube, mercury trap immersed in liquid air, McLeod vacuum gauge, mercury condensation pump, and rotary supporting pump. The tube *A* had a number of branch outlets, as shown, these being drawn out so that the tips are easily broken off. Constructions were formed in these branches at *C* so that they may be sealed off. A piece of heavy gauge rubber tubing is slipped over one of the outlets and tightly wired as shown in the figure. With a good lubricant on the glass tubing where the rubber tubing is slipped on, a high vacuum was easily obtained. When the pressure was about 10^{-4} mm. of mercury the tip *D* (which has had a nick filed about 6 mm.

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(0.25 inch) from the end) was broken off by bending the tubing. The evacuation was then continued while the filaments were kept incandescent, 150 volts applied to the plates, and the electron tube walls and especially the constriction where the electron tubes were to be sealed off were heated. This was continued until the electron tubes, being connected to receiving circuits functioned as detectors best at about 60 to 80 volts on the plate. It should be mentioned here that this is an excellent method of determining when the tube is well outgassed.

The first step in introducing the alloy after the above process has been carried out was to tip the tube *A* until a large drop of the alloy ran down thru the vertical tube into the *T* connection. Tube *A* was then sealed off at *C*. The alloy was then carefully heated until distillation took place and a thin film of the alloy condensed on the glass walls of the electron tubes. During the distilling process the filaments were kept at a dull red heat to prevent condensation of the alloy on the electrodes or stem which supports them. The electron tube is then sealed off when the vacuum gauge reads about 4×10^{-5} mm. of mercury. If a very thin film is deposited it will be of various colors, but as the film gets thicker it will attain a silvered appearance. Four tubes have been treated at one time by using a cross instead of a *T* connection.

Some tubes have been prepared by condensing only an extremely thin film of a purple color on a small portion of the walls. After use a short time the film disappears, but the tube still maintains the low plate voltage characteristics. However, the tubes containing sufficient alloy to make a permanent silvery coating on the glass walls have proven to be the most sensitive. A small amount of alloy has also been poured at high vacuum into a few electron tubes, which gave excellent results; but this is a difficult and wasteful process.

Another method which was used with fair success was to pour small amounts of alloy from the bulb of a tube similar to that of *A* into the tips of the branches. The branches were then broken off exposing the alloy to the air. This broken end was then fused onto a side outlet in the stem of the electron tube, and when the evacuation was complete the tip was heated so that the expanding alloy broke the white crust formed on its surface by exposure to air, and distilled over into the electron tube. This process is not recommended on account of the liability of the alloy taking fire when exposed to moist air.

It is extremely important to clean all glass tubing with

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"aqua regia" and distilled water so that the alloy will not stick to it. The construction at the stem or tip of the electron tube should not be less than 1.5 mm. (0.06 inch) inside diameter or the vapor will not distill thru it easily. It will usually be found necessary to distill the vapor progressively by heating gradually toward the opening of the electron tube. The constriction should be heated slowly until it is free from all condensed alloy before sealing off or the glass will crack after cooling. Too much heat will burn the alloy, giving it a dark brown color.

The potassium sodium alloy should be prepared by putting sodium and potassium into a glass tube in the proportion of 23 gms. sodium and 39 gms. potassium; then the tube should be quickly exhausted and sealed. Heat should be then applied to the sodium and potassium until it fuses and mixes. The containing tube should be provided with a connecting tube with a very small hole in the connecting neck. The fused mixture can can be poured thru this hole into the connecting tube which process filters it. This second tube should be provided with a drawn down stem and constriction so that the alloy can be transferred into the containing tube *A* of Figure 1 by a process similar to the transfer of alloy into the *T* connection as described.

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THERMIONIC TUBES*

By

Frederick S. McCullough

(Westinghouse Electric and Manufacturing Company, Pittsburgh Pennsylvania)

Quite a number of years ago, Mr. Edison brought before us an experimental lamp novelty consisting of a glass bulb containing a filament and a plate with the air exhausted. Later it was applied in a new art—now known as radio. Quite recently a third element was added, which was called a grid. Since that time there have been great strides made in this country and abroad by scientists and engineers in developing this device from a toy to a powerful instrument for uses in high power circuits.

The earlier tubes were first used as detectors and later as amplifiers, until it was found that they could be used as oscillation generators and power amplifiers. The life of these old tubes was very short, owing to the presence of gas which in time destroyed the cathode. Since that time some difficult problems have been solved in the development of these tubes.

The first one which will be taken up is the production of high vacuum within these tubes and the effect it has on their operation. Methods for production of low pressures have been devised by several people and excellent results have been obtained. I do not intend to dwell on any definite method of producing an extremely low pressure, but what I am trying to bring forward is that even if we have exhaust means for producing pressures as low as 10^{-7} bars or lower, we are still confronted with the space pressure surrounding the elements within the tube while under operation. Very little information is available concerning this point. If we exhaust a tube by baking the vessel at a temperature close to the collapsing point of glass, and then measure the pressure, we find that we have produced a vacuum as low as it is possible to obtain. We next heat up the metals within the vessel. These give off gas, thus changing the pressure. We repeat this continually by raising the plate temperature, either by radio frequency,

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induction, or bombardment. The induction method I will take up later on, but the bombardment method I will describe here.

We first heat the filament—apply a positive potential on the plate and alternating potential on the grid. We will notice that there is considerable ionization present. If the vessel is of glass it is best to keep it extremely hot. I wish to emphasize that this is a method for producing tubes without the use of a "getter." By "getters" we mean the substances such as phosphorus, arsenic, sulphur, and so on. These substances, when applied to the metals and volatilized by heating them, trap the gases. They are then deposited on the walls of the tube as a film. Whether the presence of this gas containing film is reliable when working high temperature tubes is questionable. We are building tubes of extremely high capacities and it is quite obvious that we have to get rid of all the gas possible and not have the vessel contain any film holding gases.

Many interesting phenomena are observed with slight residual gasses always present even in the hardest of tubes. After running for some time with an electron current to the plate at a fixed voltage, a steady value for the pressure may be reached. If the voltage is increased, but not sufficiently to overheat the plate, the tube will harden. If the filament alone is simply heated and no potential applied to the plate, we find that the residual gas has increased. When a filament is heated and no potential applied to the plate, the tube pressure would be equally distributed thruout the vessel, except for a minute space surrounding the filament. If we apply a potential to the plate we produce a field surrounding the filament created by the electron emission. This field has a much lower gas pressure than the remaining portion of the vessel. This leads to the conclusion that these effects are due to ionized gas. At these voltages the ions are positive and their observed disappearance must be due to the fact that they are driven into the walls of the vessel. Some suggestions have been made that they are driven into the filament, but how can they be if they must be retained with the filament at 2,000°C.? So it seems advisable to give up the theory that they return to the filament.

Much data have been supplied by different investigators of the clean-up of gases, and from conclusions drawn it seems that high temperature devices clean up much more readily. For instance, take the clean-up of the tube containing a coated cathode. An experiment with this type has been made wherein the whole tube was immersed in liquid air. The electron current was maintained constant. Clean-up was slow, probably owing to the slow

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saturation of the walls of the tube with the gas. To facilitate a more rapid clean-up, I have placed a tungsten filament within a tube of this character, shielding the coated filament by the grid support so as to prevent the high temperature from affecting the coating on the filament. In this case liquid air was not used, letting the walls of the vessel heat up so that the gases would penetrate at this temperature. When the tube was sealed off from the exhausting means, the glass contained the gas trapped at this high temperature. I found the rate of clean-up was about the same as for a tungsten filament tube. Further, a coated filament tube which would previously work at 2,000 volts, would function properly at several thousand volts higher.

A conclusion can be drawn that coated filament using the bombardment means and other low temperature means of clean-up places them in a low voltage condition. I have not indicated any particular gas or pressure in these experiments, but merely have expressed a method which may be used, because of confusion which may arise and elaborate descriptive matter which would be required thoroly to identify any particular gas.

To produce tubes of the highest possible quality, we first have to consider what type of a tube we wish to construct. If it is a tube for receiving purposes it naturally will be of small dimensions. In case of building a tube of small dimensions we would choose for its container ordinary soft glass. The metals have to be of such a nature that under normal working conditions they will not heat themselves or the glass to such a temperature as to spoil the operation. The operating voltage must also be considered. If we take an ordinary receiving tube and apply a certain plate potential and no grid bias, we would normally consider a tube good which showed less than a micro-ampere negative grid current. Let us consider a tube of this type with its filament grid and plate, such as the Westinghouse coated filament W.D.-11 described below. We find that there is still a slight presence of gas in this tube which cannot be measured on a microammeter. This being the case, we use in this tube a filament with the least possible watts, so as not to heat the space surrounding this filament, and also use a plate potential that will not disturb the extremely small amount of gas present. To make a comparison, I will illustrate a tube such as the Westinghouse W.T-22 (see description below), which has a greater spacing between its elements. It also has a higher filament watt consumption and a higher plate potential. A tube with such space relations can be used as a power amplifier while having as much as half a micro-ampere negative grid current and

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yet has a straight characteristic curve. Consider the development of still larger tubes, such as power tubes,—for instance,the Westinghouse W.T-24. Its normal rating is 250 watts. That is, it will consume 500 watts on the plate working at 50 percent efficiency. It will supply 250 watts oscillating energy or 250 watts modulated energy with a certain grid bias. Consider tubes of this character under working conditions,—two used as oscillators and three as modulators, using the constant current system of modulation. We find that under best conditions the

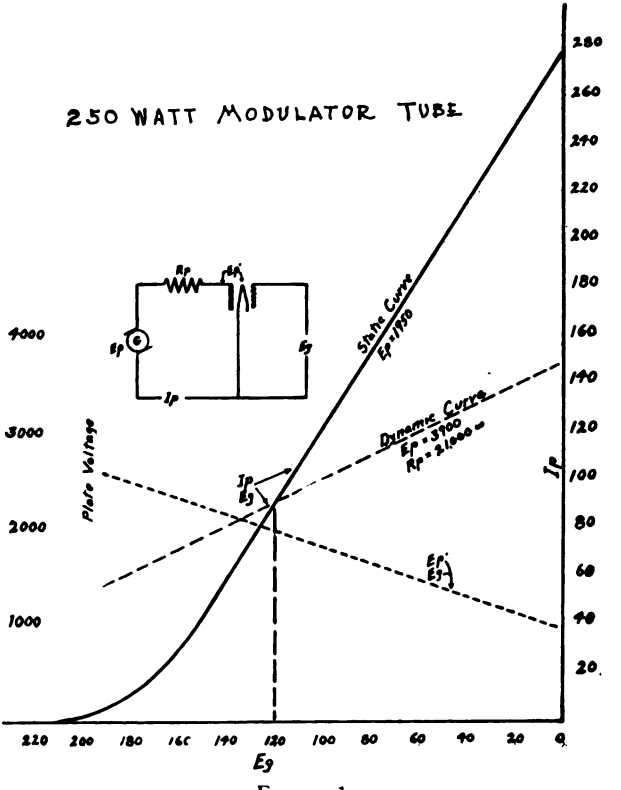

FIGURE 1

modulator tube power consumption should be the same as the oscillators, and the dynamic characteristic of these modulators should be such that the grids will not go positive when 80 percent or 90 percent modulation is desired. Great care must be taken in the design of such a tube. It must be a power-wasting device and still have good control.

There is one feature which must be especially cared for. That

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is the presence of gas. It must permit a current value in the neighborhood of not over 10 micro-amperes in the grid circuit. This may seem extremely low in comparison to some tubes which are being produced, but, nevertheless, the grid current is one of the greatest factors in giving good modulation. If you do not have an extremely low grid current, the modulator will oscillate at a radio frequency and will not parallel. Take three tubes all having the same characteristics. We place the tubes in a circuit at 2,000 volt plate potential, 125 volts grid bias, and find that we get 150 milliamperes plate current thru each. When we start to

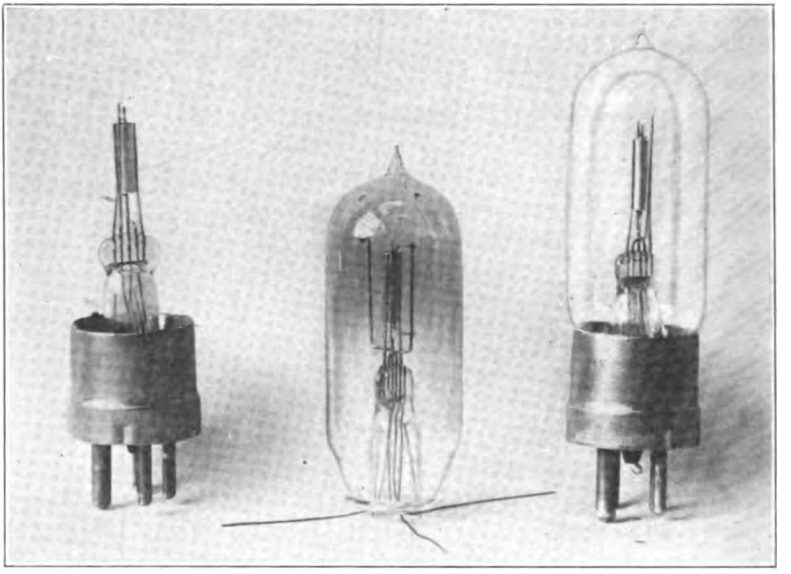

FIGURE 2

modulate at a certain frequency, the tubes will "shoot over" or start oscillating at an extremely high frequency, due to some disturbance. This action is further increased by adding more modulator tubes. To overcome this difficulty, when other tubes are not available, high frequency choke coils may be added in the plate circuit of each tube.

We have mentioned several tubes manufactured by the Westinghouse Company. It seems appropriate to give a description of their constructions and characteristics. The W.D-11 is a high vacuum tube which is used as a detector or amplifier, either audio or radio frequency. It has a particular application in the Radiola Senior and another in the Radiola Grand, both manufactured by

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the Westinghouse Company. In this latter application one tube is used as a detector, three others as amplifiers at audio frequency. The detector is used at 22.5 volt plate. The amplifiers are operated at 45 to 65 volts. The filament consumption on these tubes is about 0.25 ampere at one volt, and suitable for operation on a single dry cell or on two Edison Leland primary cells (as in the Radiola Grand). The tube requires no grid bias. This tube is made as follows: The container is a soft glass bulb, sealed in a special four prong base, which makes it non-interchangeable with other types of tubes. A nickel plate 0.005 inch (0.013 cm.) thick is made into a cylinder $\frac{1}{8}$ inch (0.32 cm.) diameter and $\frac{5}{8}$ inch (1.6 cm.) long. The grid is a cylindrical helix $\frac{1}{16}$ inch

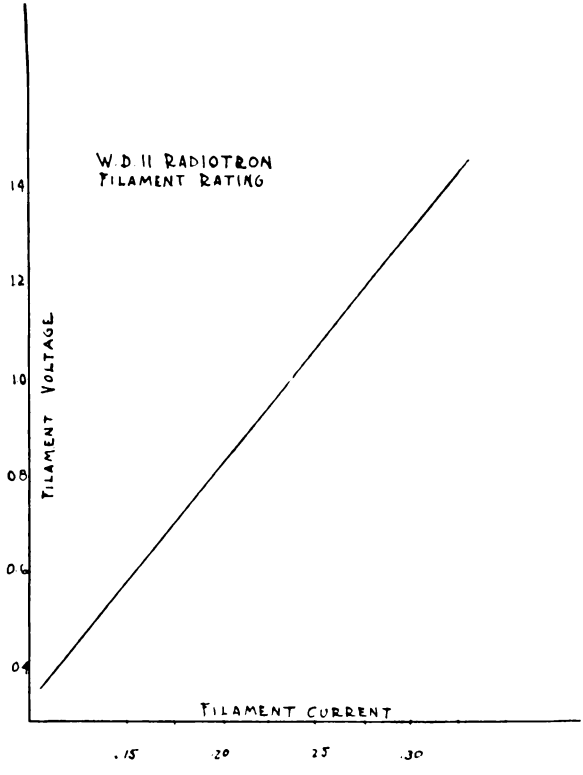

FIGURE 3

(0.16) cm.) diameter made of 0.014 inch (0.036 cm.) nickel wire. The filament is a platinum iridium strip 0.00025 inch (0.00064 cm.) by 0.005 inch (0.013 cm.) and $\frac{5}{8}$ inch (1.6 cm.) long, coated by a special process with a barium and strontium oxide. This fila-

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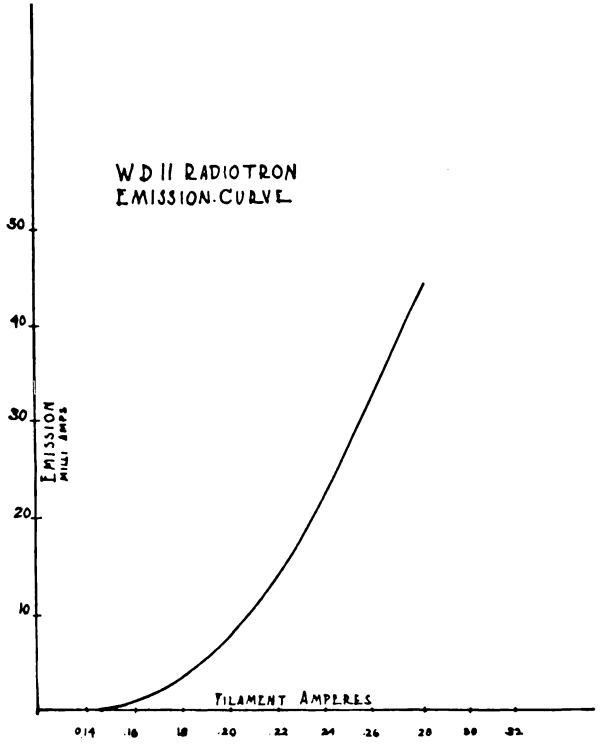

FIGURE 4

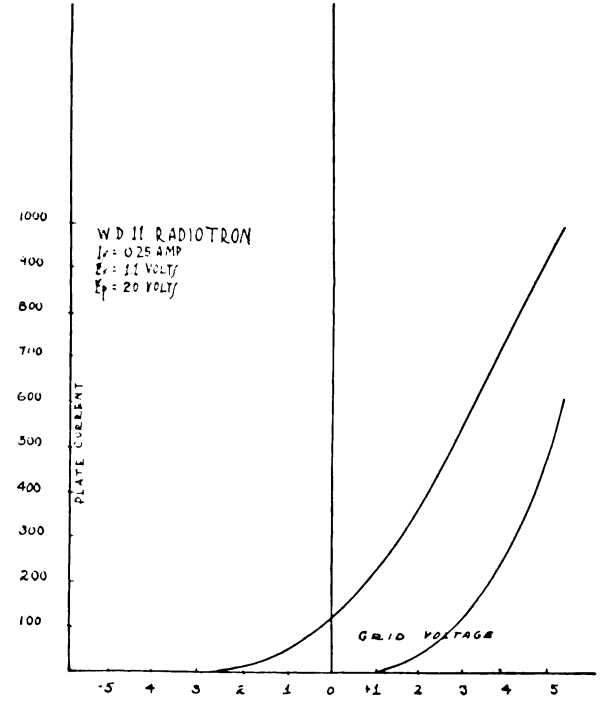

FIGURE 5

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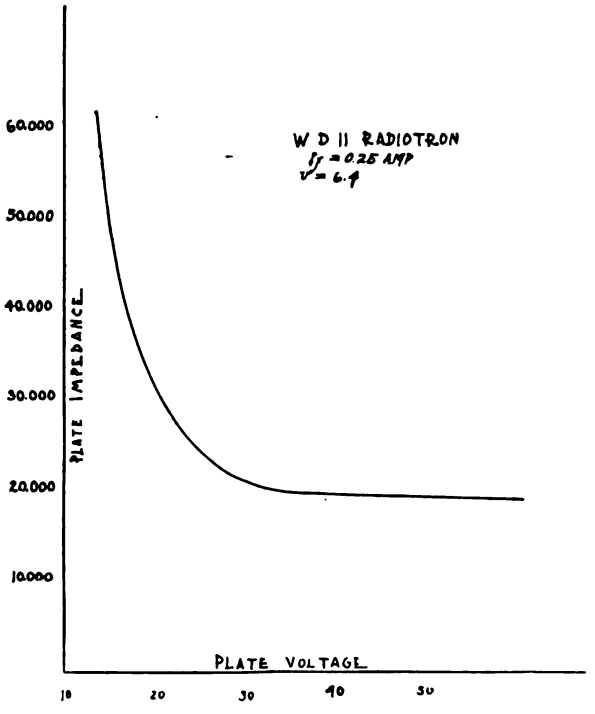

FIGURE 6

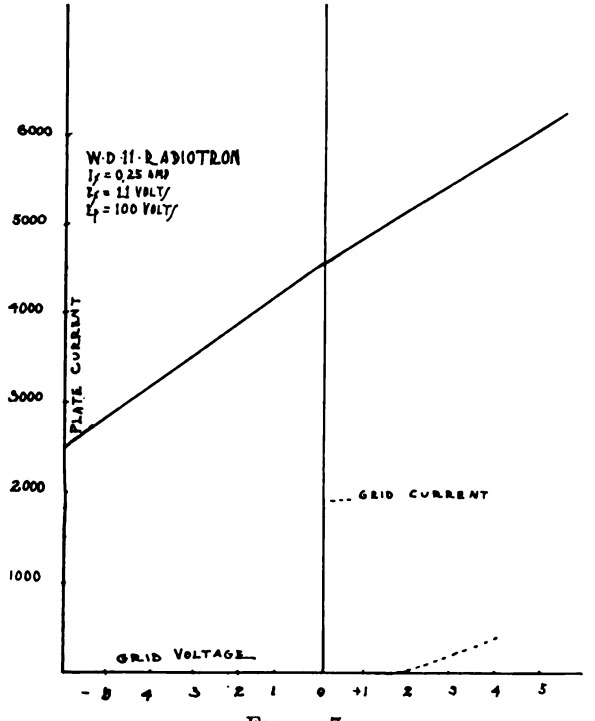

FIGURE 7

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ment is held under tension by a spring. All parts are supported from a single press on nickel wire. The tubes are evacuated by a specially timed process. Induction beating is used to secure the complete removal of gasses without injury to the delicate coated filament.

The tubes are tested for grid current and filament potential. In addition, an amplification test determines by actual measurement the amount of audio frequency energy obtainable for certain grid excitation.

The tube called W.T.-22 is a 5-watt power tube used as an amplifier or an oscillator in small sets. It can be operated at 7 volts on the filament drawing about 1.25 amperes. The plate will operate on voltages from 100 to 500. The plate current is from 10 to 50 milliamperes.

This tube is placed in a soft glass container slightly larger than W.D-11 and mounted in a standard Navy type base.

The plate is 0.005 inch (0.013 cm.) molybdenum built into a rectangular box like shape, 7/8 inch (2.23 cm.) long and 3/4 inch (1.9 cm.) by 1/4 inch (0.64 cm.) wide. It is held on nickel supports.

A helical grid is made of molybdenum wire welded to molybdenum supports, and conforms to the shape of the plate. The filament is M-shaped and held on tungsten supports. It is made of a platinum iridium alloy coated similarly to W.D-11.

W.D-24 is a power tube used as an oscillator on a 2,000 volt direct current circuit. The filament is rated at 15 amperes at 10 volts. The plate current can go as high as 250 milliamperes.

This tube is built in a hard glass container 14 inches(35.6cm.) long and 5 inches (12.8 cm.) in diameter. The grid and the filament are supported from the lower press, the plate from the upper press.

The plate is oval shaped, made of two halves joined together as two ribs. The grid conforms to this shape. The filament is V shaped and held under tension by a spring from the upper press.

Plate and grid are made of molybdenum. The filament is of tungsten. All the supports are of molybdenum. The leads are of tungsten.

W.T-25 is a modulator tube very similar to W.T-24, but with a lower plate impedance and a straight line characteristic.

The writer is also exhibiting samples of a 5 kilowatt, a 10 kilowatt, and a 25 kilowatt tube. The 5 and 10 kilowatt tubes are built in hard glass containers of suitably large size. They conform in general character to the W.T-24 except for their plate voltage, which is 10,000 to 20,000 direct current.

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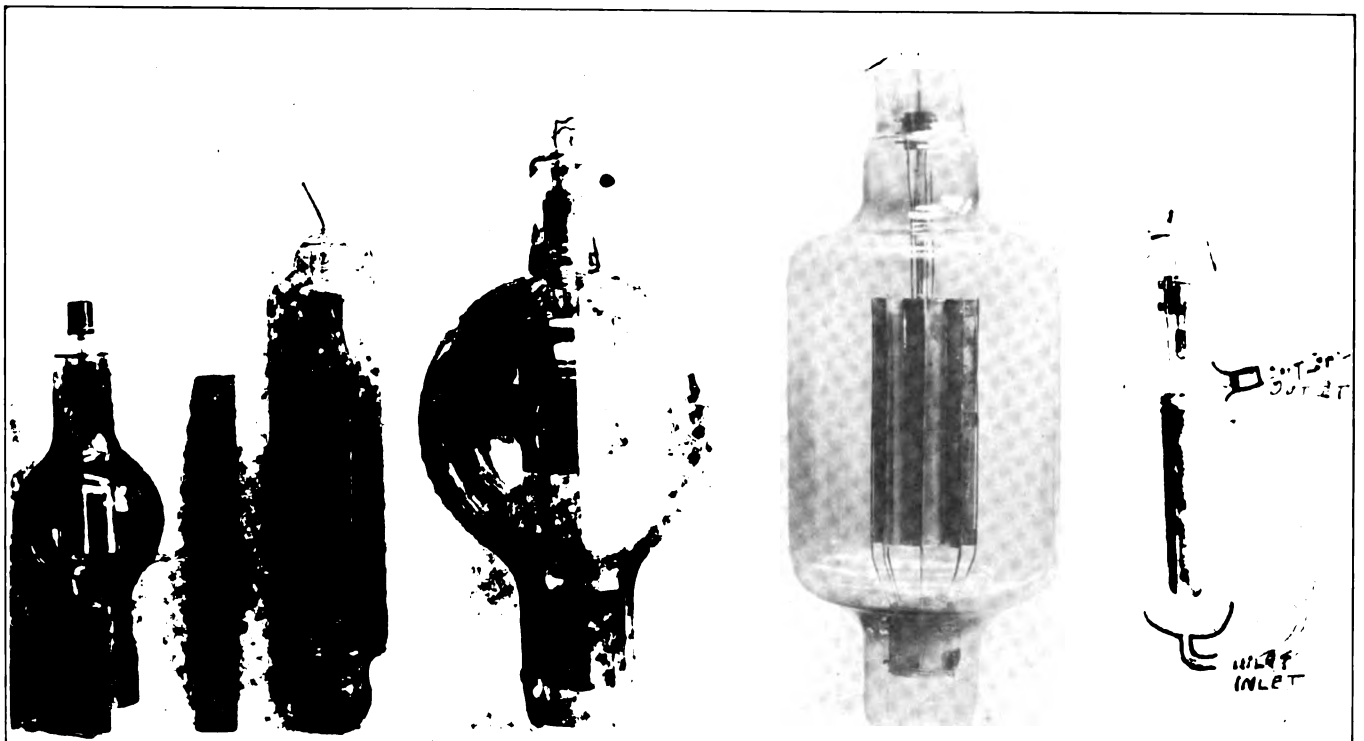

250 Watt Oscillator | 1 Kilowatt Rectifier | 5 Kilowatt Oscillator | 10 Kilowatt Oscillator | 25 Kilowatt Metal Tube Water Cooled

FIGURE 8

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The 25 kilowatt tube has a plate sealed in the glass and forming part of the container. The glass serves only to insulate the filament and the grid leads. The plate is water cooled on the outside and is capable in this way of dissipating up to 10 kilowatt. This tube can be operated at 20,000 volts direct current with more than 2 amperes plate current.

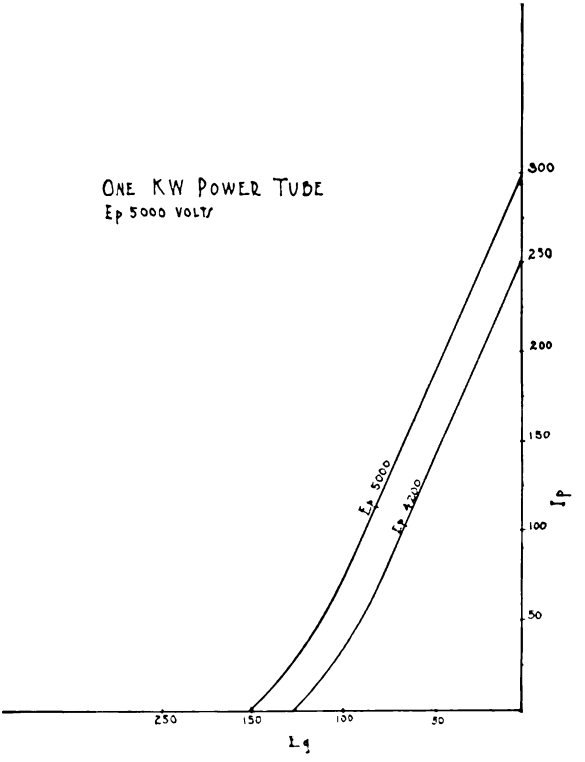

FIGURE 9

To produce tubes which have no negative grid current present is quite an interesting problem, which I believe has been quite satisfactorily solved by a method known as pre-treating of elements. The best method we have found is to heat the metals approximately up to their melting point within a vacuum furnace. In 1914 or 1915 the Western Electric Company made for their Arlington transmitter some special tubes. These tubes had a ribbon bent back upon itself, forming an oblong plate. Each end of the ribbon had a lead wire brought out. A current was passed thru this ribbon to heat and drive out the gas.

About this time the writer invented heating by high fre-

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quency.* Since then new applications have arisen. The writer will now endeavor to explain the use of this method in several applications.

Power tubes have had a number of limitations. The capacities of these tubes were limited by the size of the cathode. The energy consumed in the cathode was extremely high relative to the space energy, that is—the energy dissipated in the plate and filament circuit. This formed the limit of the capacity of the tube. These

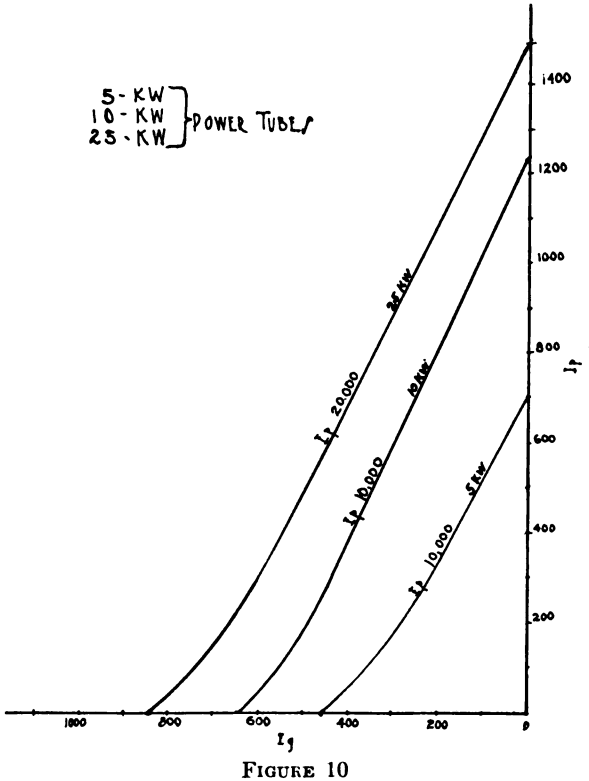

FIGURE 10

limitations made it necessary to reduce the plate current and raise the plate voltage. High voltages in power tubes are accompanied by electrostatic stresses. High frequency oscillations are liable to puncture the glass under these conditions. The limit of plate direct current voltage is about 10,000 to 20,000. It is evident that the problem of raising the capacity hinges essentially on high filament emission for certain energy input.

* Patent application, serial number 128,375 of October 30, 1916.

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To facilitate the electron emission the cathode may be coated with oxides. By this method it is possible to reduce considerably the watts input to cathode and get the same emission. A cathode of this nature has smaller dimensions and therefore the means of support are simpler and the lead-in wires are made smaller. Since the voltage drop thru the cathode is limited, the leads to supply the energy to tungsten cathodes are large and unwieldy. Coated cathodes require either a much smaller lead-in wire or else the same lead-in wire will permit much larger electron emission. The writer will show below how the leads can be omitted altogether. This is accomplished by heating at radio frequency. A compact cylindrical cathode possesses all the advantages and none of the disadvantages of the usual type of cathode.

It is well known that at higher temperatures the escape of occluded gases destroys the vacuum. A coated filament will keep all parts of the tube below a safe temperature, that is, a temperature which will not liberate occluded gases.

A peculiar phenomenon has been observed where the filament supports were not specially treated. It appeared that as soon as heat was applied to the filament a certain amount of gas showed in the tube. This undoubtedly came from the supports. The gas was in only very minute quantities, yet it had a secondary effect on the filament. Hot spots appeared on the plate, presumably due to corresponding high temperature points on the filament. It is conceivable that the filament would undergo a bombardment by positive ions with a consequent volatilization of metal and creation of hot spots.

The presence of volatilization in a device which has a large coated cathode area many times larger than an ordinary tungsten filament would be quite minute. As previously mentioned, the presence of gases or positive ions is indicated by a grid current. To prevent the presence of positive ions and volatilization, it is quite necessary to have the metals free from gases before enclosing them within the vessel. This is accomplished by heating them up to approximately their melting point in a vacuum furnace.

The usual methods of heating the filament have been direct or alternating current. The use of radio frequency permits a number of changes in design, simplifying the structures and increasing the rigidity of filament. In order to obtain a strong filament construction able to withstand the ionizing forces and subsequent handling, a thick rugged filament is always used in high power tubes. This means a large heating current and thick lead-in wires to carry this current. The glass surrounding thick lead-in

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wires is subject to severe strains, with liability to fracture. The employment of radio frequency cathode heating makes it unnecessary to carry heavy current thru the glass.

Figures 11 and 12 show two types of construction developed by the author, using radio frequency heating. In Figure 11 the coiled plate carries radio frequency current and induces by transformer action a large current in the centrally located cylindrical cathode. Figure 12 shows a separate inductor located on the outside of the tube and a cylindrical plate split in an axial direction. No lead-in wire is required in Figure 12. In Figure 11 only thin leads are necessary,—sufficient to carry current to induce heating in the cathode. By supplying a sufficient number of convolutions in the inductor the current thru the lead-in wires can be made very small.

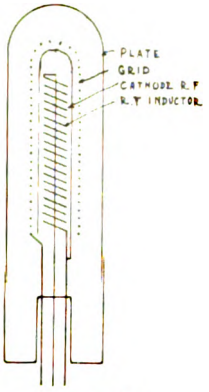

FIGURE 11
Interior of Inductor Heated Cathode Tube

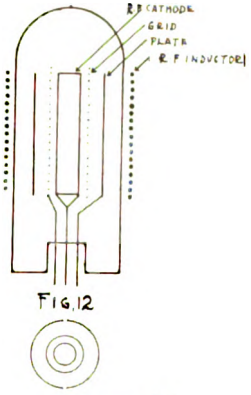

FIGURE 12
Plan of Exterior Inductor Heater Tube

Figure 12 is an example of an equi-potential electrode tube. Such a tube would possess marked advantages when used as an oscillator, power amplifier, or rectifier.

In Figure 13 is shown a rectifier having a plate and a tungsten filament. In this circuit it will be seen that the electron flow is densest towards the negative side of the filament. When the contact R is at the point V on the resistance VZ, the galvanometer G will register a slight thermionic current, but the latter will be very small. As R moved along VZ, this current is rapidly increasing, partly because a greater portion of the filament is coming under the influence of the plate and partly because the attractive force, represented by the plate potential, has also been increased.

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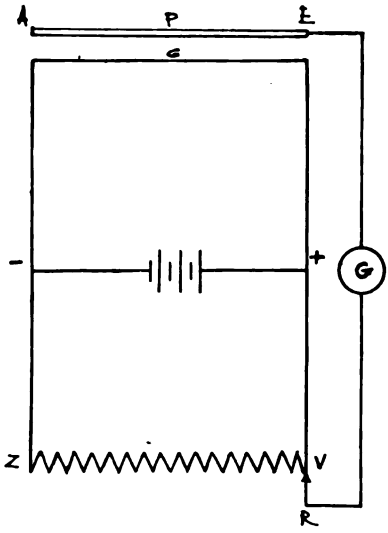

FIGURE 13

From the above consideration we see that:

(1) If an electrode within a vacuum is connected directly to the negative end of the filament, there will be no tendency for an electron flow to be established.

(2) If the electrode is connected directly to the positive end of the filament, electrons will flow from every part of the filament to it, since it is at a higher potential than the filament. Most of the electron current will come from the negative end of the filament since it is there that the potential difference between electrode and filament is greatest. The potential of the electrode will be positive and equal to the emf. across the filament.

(3) If the battery supplying the filament is shunted by a resistance which has a variable contact sliding along it, and the electrode is connected to the sliding contact, the potential of the former may be varied between zero and a positive value equal to the emf. of the battery. The electron flow to the electrode will gradually increase as the sliding contact is moved towards the positive end of the resistance.

The potential gradient along a filament is always a complication, altho practical advantage is often taken of it. It becomes a serious factor when the voltage across the filament is say 30 volts—as may be the case in a large tube. Another important effect is the variation of temperature along filaments.

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Normally the temperature along a filament is uniform, except at the ends where cooling takes place. However, when there is a plate current, this current adds itself to the filament current and causes one half of the filament to be hotter than the other. This may be shown by arranging a circuit similar to the one shown in Figure 14. The plate circuit may be completed by closing a switch. Between the negative end B of the filament and the battery A is connected an ammeter G_1. Between C and A is another ammeter G_2.

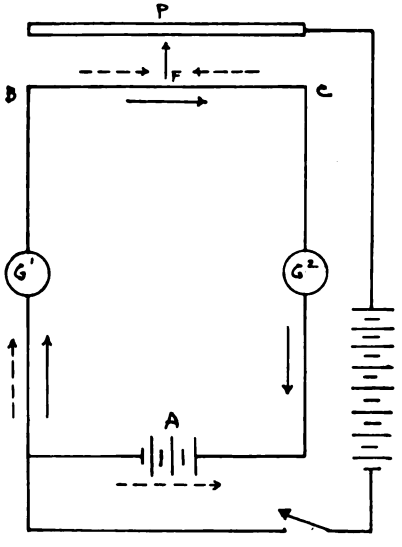

FIGURE 14

If we leave the switch open we will see that the filament current readings G_1 and G_2 are the same. Suppose the filament current flowing in the direction of the arrow-heads is 1 ampere as registered by both ammeters, on closing the switch it will be noticed that the reading in G_1 will increase above 1 ampere, while that of G_2 will decrease below that value.

The phenomenon is explained by the existence of an electron current in the plate circuit which flows round by H and the switch and divides at the connection to the filament. Part of the electron current flows via G_1 to the filament and thence to the plate, as shown by the dotted line arrow-heads. It therefore reinforces the filament current from the battery which is flowing in the same direction. Another portion of the thermionic current flows via A, G_2, C, the filament, and thence to the plate. This current opposes the existing filament current and causes a reduction in the

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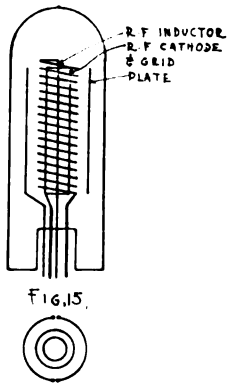


FIGURE 15
Plan of Grid Inductor Heater Tube

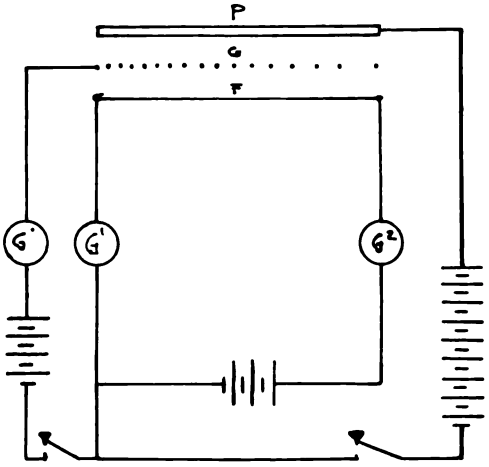
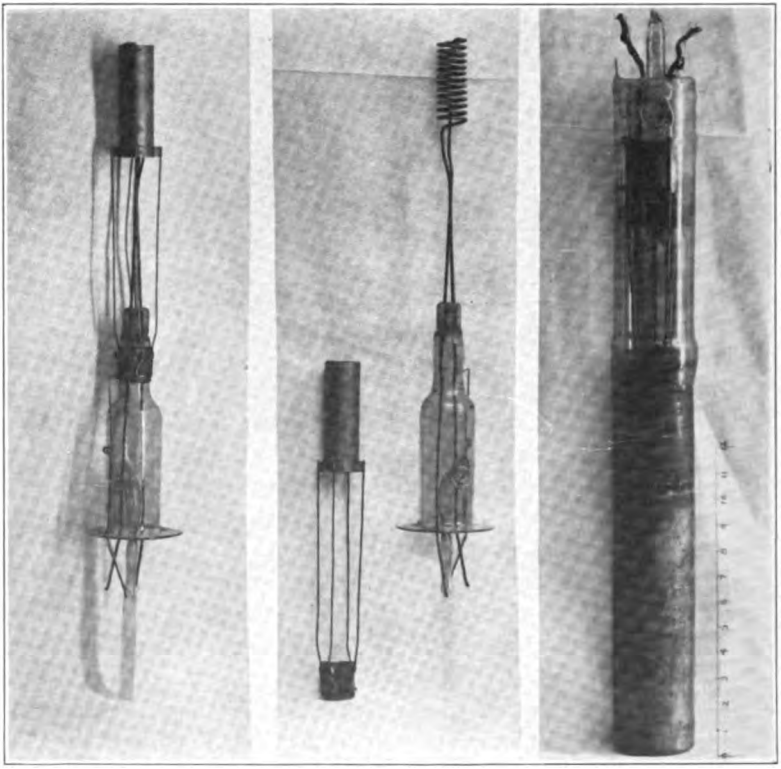


FIGURE 16
A Grid in a Tube which Has Filament Drop Should Be Spaced Accordingly



Radio Frequency Heated Cathode, Assembled

Radio Frequency Cathode

Radio Frequency Inductor

100 Kilowatt Radio Frequency Heated Cathode Tube

FIGURE 17

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current passing thru G_2. The result is that the negative half of a filament is always hotter than the positive half, no matter to which side of the battery the negative of the plate battery may be connected. In practice this peculiar effect is of no importance except when the temperature of the filament is already near melting point and the plate current great. Under such conditions the filament is likely to burn out when the plate circuit is completed.

From the above considerations the advantages of an equipotential emitting surface are evident.

The writer has constructed and operated tubes of this description. They show the possibilities of large electron emission and one line of future progress in high power tubes.

SUMMARY: The general scope of the paper covers the present day commercial tube; states the methods of design; and gives the general dimensions. It later brings forth an entirely new method for obtaining electron emission and control. This new method of heating provides means for heating sheets or discs of tungsten or other high temperature metals to incandescence, which sheets or discs are enclosed in evacuated vessels or ones containing gas.

The tubes in which the grids are made the inductor to heat the cathode provide a radio frequency method for shutting off the current twice per cycle, and gives a double frequency in the output circuit. By these new methods set forth in the paper, it is evident that the tube engineering art will be greatly benefited.

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DIGEST OF UNITED STATES PATENTS RELATING TO RADIO TELEGRAPHY AND TELEPHONY*

ISSUED AUGUST 29, 1922-OCTOBER 24, 1922

BY

JOHN B. BRADY

(PATENT LAWYER, OURAY BUILDING, WASHINGTON, D. C.)

1,427,350—J. Bethenod, filed September 2, 1919, issued August 29, 1922.

RADIO TELEGRAPHIC COUPLING for use with a radio frequency alternator wherein the armature winding is divided in the several sections, each of the sections being connected directly to a primary winding of separate transformers, and the secondary windings of each of the transformers connected with an antenna ground system. The central point of each section of the alternator and the central point of each primary winding is grounded.

1,427,832—F. S. McCullough, filed July 7, 1919, issued September 5, 1922. Assigned to Glenn L. Martin.

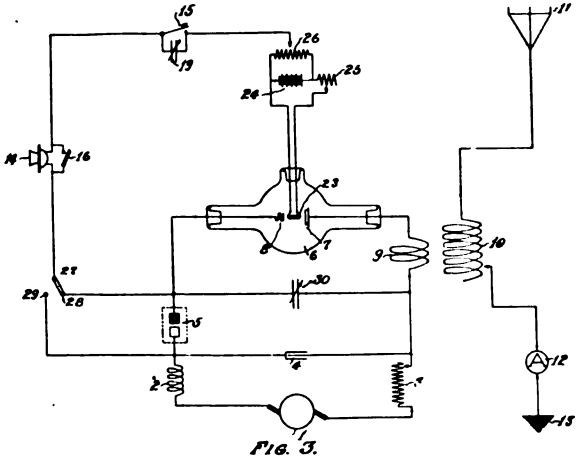

FIG. 3.

NUMBER 1,427,832—Radio Telephony

*Received by the Editor, November 3, 1922.

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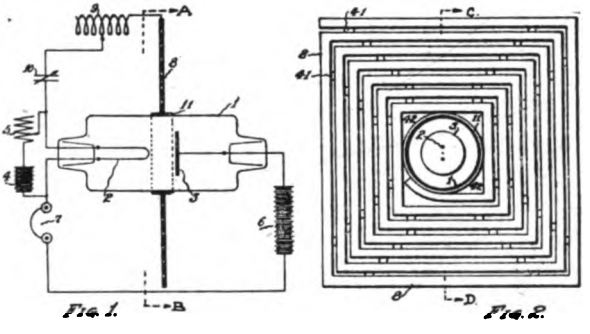
RADIO TELEPHONY. This patent shows an adaptation of an arc generator as a source of oscillations for a radio telephone transmitter. The invention includes a high frequency spark gap placed in series with the arc to serve as a stabilizer, filter, buffer, or equalizer for the irregular oscillations inherent with the arc generator. The high frequency spark gap comprises a tube containing an inert gas, an anode and a cathode between which the stabilizing arc is formed, and a control member in the form of a third electrode between the spark gap electrodes which is connected in circuit with a microphone or other form of modulator. The oscillation circuit is inductively coupled with an antenna ground system.

1,427,833—F. S. McCullough, filed August 2, 1919, issued September 5, 1922. Assigned to Glenn L. Martin.



NUMBER 1,427,833—Radio Telegraphy

RADIO TELEGRAPHY. This invention relates to a construction of directional radio receiving apparatus. The receiver includes a vacuum tube containing a filament and a plate with a flat spiral coil surrounding the tube exteriorly and having its plane perpendicular to the axis of the tube. The flat coil serves as a collector of the transmitted energy and has the characteristics of a loop in the sense that it is aligned with the distant transmitting station with the axis of the tube perpendicular to the line joining the transmitting and receiving stations. The collector is mounted upon a ring or band fitting on the vacuum tube positioned intermediately of the electrodes within the tube. A tuned circuit is connected with the coil collector and the telephone receivers placed in the circuits including the electrodes within the tube.

1,428,156—L. Espenschied, filed September 26, 1919, issued

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September 5, 1922. Assigned to American Telephone and Telegraph Company.

Low-Frequency Amplifier illustrated in connection with a line wire system comprising a plurality of tubes successively arranged in balanced relation with a modulating device connected to the incoming circuit and the amplifier connected in the output circuit of the modulating device. A de-modulating device has its input circuit connected to the output circuit of the amplifier and the output circuit of the de-modulator connected to the line. A source of alternating current of a frequency suitable for amplification by the amplifier circuit is connected to the input circuit of the modulating device and the output circuit of the de-modulating device.

1,428,507—E. A. Sperry, filed March 12, 1920, issued September 5, 1922.

Radio Repeater System. This invention relates to a system for automatically transmitting the readings of an indicator, such as a compass, a fire control instrument on board a ship, or other form of dial indicator, and reproducing the readings at a distant receiver. The transmitter circuit and receiver circuit are arranged so that a step by step mechanism at the transmitter controls the movement of a step by step mechanism at the receiver. The transmission of impulses at one frequency may move the step by step indicator in one direction at the receiver while the transmission of impulses of a different frequency may move the indicator step by step in the opposite direction, thereby controlling a dial at the receiver in accordance with the movement of the dial at the transmitter.

1,428,856—L. O. Parker, filed May 13, 1918, issued September 12, 1922. Assigned to Westinghouse Electric and Manufacturing Company.

Spark Gap Apparatus. This invention is directed to the construction of a rotary spark gap wherein the rotor comprises a toothed disk co-operating with a stationary electrode, the stationary electrode being mounted circumferentially adjustable and radially adjustable with relation to the rotary electrodes.

1,429,227—W. Dubilier, filed September 28, 1921, issued September 19, 1922. Assigned to Dubilier Condenser and Radio Corporation.

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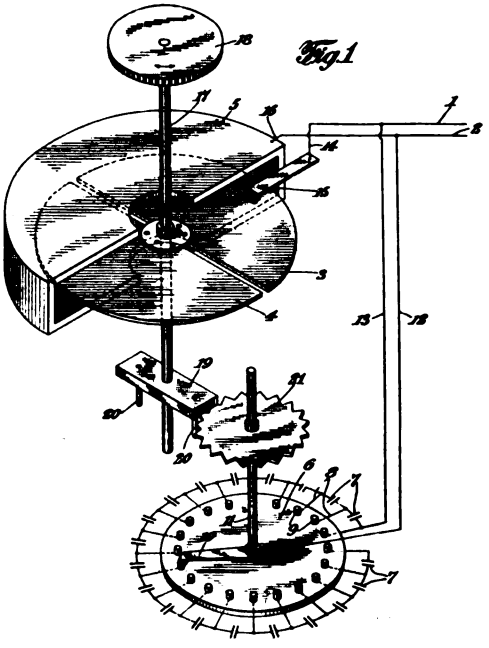

NUMBER 1,429,227—Variable Condenser

VARIABLE CONDENSER, comprising a plurality of fixed condensers arranged with intermediate connections to a set of contacts, and a variable condenser having a control for changing the position of the variable plates simultaneously with the cutting in of a predetermined number of the fixed capacities. The variable condenser is made in two parts having semi-circular plates arranged to be shifted in such manner that just prior to the time when the fixed condenser is shifted from one value to the adjacent value one of the parts of the variable condenser may be shifted to approach maximum capacity value and the other of its parts shifted to main capacity value, and at the instant the fixed condenser is adjusted, the part of the variable condenser which is at maximum is cut out of the circuit and the part which is of minimum capacity value is substituted in circuit therefor.

1,429,240—E. C. Hanson and E. T. Jones, filed February 24, 1920, issued September 19, 1922.

RADIO SIGNALING SYSTEM, utilizing an underground antenna system having concentrated capacity areas buried in the earth and connected to the radio signaling apparatus. The capacity

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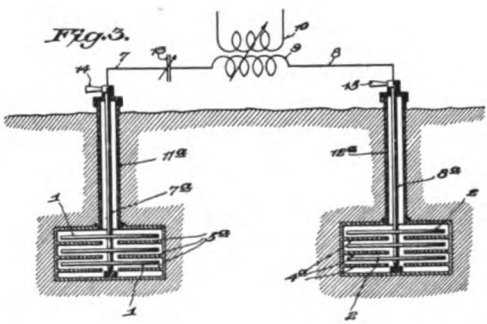
areas are constructed so that their mutual capacity areas resemble in principle the usual variable condenser in that the stationary metallic plates are formed in a casing buried in the earth and rotary plates arranged to be intermeshed with the stationary plates. The rotary plates are secured upon a shaft which may be revolved from the surafce of the earth under control of an operator. The object of the invention is to secure a concentrated capacity area giving the same effective capacity as a long buried underground wire and at the same time provide a means for securing an equivalent optimum wire length by adjusting the position of the rotary plates.



NUMBER 1,429,240—Radio Signaling System

1,429,497—R. A. Fessenden, filed June 6, 1917, issued September 19, 1922. Assigned to Submarine Signal Company.

METHOD AND APPARATUS FOR DETECTING, MEASURING AND UTILIZING LOW FREQUENCY IMPULSES existing in a circuit with high frequency impulses which consists in passing the low frequency impulses together with the undesired high frequency impulses thru an amplifier, the amplification constant of which is the function of the ratio of the frequency in the amplified circuit to the frequency of the current to be amplified, and employing as the frequency of the amplified circuit a frequency of the order of one thousand per second, whereby said low frequency comparatively inaudible impulses are highly magnified and rendered audible, while said undesired high frequency impulses are substantially weeded out.

1,429,634—C. Robinson and R. M. Chamney, filed November 18, 1919, issued September 19, 1922.

TELEPHONIC REPEATER, including a three-parallel core magnetic structure with line windings on two of the cores and a

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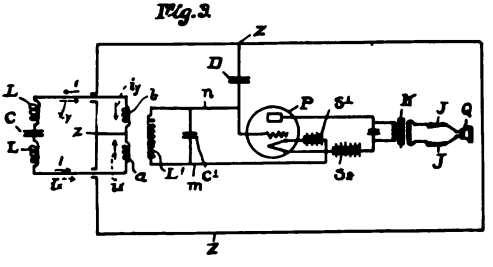
booster winding in two equal halves in series to assist one another on the same cores connected with the output circuit of an electron tube. A winding on the other core is connected in the grid circuit, the complete assembly serving as a current amplifier.

1,429,858—E. C. Fasoldt, filed April 7, 1922, issued September 19, 1922. Assigned two-thirds to Louis R. Krug.

RHEOSTAT for securing fine adjustment in values of resistance for such purposes as heating filaments. The resistance is spirally wound and the contact element may be turned axially to reach any point on the turns of the coil.

1,429,572—Henri Jean Joseph Marie de Regnauld de Bellescize, filed August 14, 1918, issued September 19, 1922.



NUMBER 1,429,572—CIRCUIT RECEIVER

CIRCUIT RECEIVER. This invention has relation to the balancing of the dissymmetries existing in the usual coupling in a radio receiver. The patent points out the disadvantages of dissymmetries at a receiver, that is, the impossibility of sharp tuning for one predetermined transmission and the impossible elimination of very powerful waves of a different length from that of the waves which are to be received. The disadvantage of the undesired oscillations at the receiver is also discussed. The responsiveness to strays and atmospherics is another drawback largely accountable to dissymmetry in the circuits. In this invention the connections between the condenser C' and the ground are rendered symmetrical, and the two parasitic actions existing between primary $L\ C$ and secondary $L'\ C'$ are nullified by circuit connections shown, thereby securing the desired symmetry of circuits.

1,430,256—E. S. Pridham and P. L. Jensen, filed August 21,

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1917, issued September 26, 1922. Assigned to Commercial Wireless and Development Company.

METHOD OF AND APPARATUS FOR TELEPHONICALLY TRANSMITTING SPEECH, in an environment of extraneous noises such as aircraft radio telephone transmission. The method claimed consists in balancing the noise in the transmitter to maintain a static condition of the telephone circuit normally and to direct speech into the transmitter in such manner that it is unopposed.

1,430,257—E. S. Pridham, filed May 7, 1918, issued September 26, 1922. Assigned to The Magnavox Company.

TELEPHONE TRANSMITTER, constructed with a perforated casing surrounding the variable resistance transmitter element whereby free access of sound vibrations is permitted to both sides of the diafram.

1,430,258—E. S. Pridham, filed December 26, 1918, issued September 26, 1922. Assigned to The Magnavox Company.

TELEPHONE TRANSMITTER, arranged for balancing out extraneous sounds. A transmitter button is connected by an arm with a diafram so that sounds have access to both sides of the diafram and sounds that have access to but one side of the diafram produce their full effect on the transmitter button.

1,430,607—W. C. White, filed October 31, 1917, issued October 3, 1922. Assigned to General Electric Company.

CONSTANT RESISTANCE ELECTRON DISCHARGE DEVICE. This patent is directed to a circuit of an electron tube whereby the tube has a constant resistance characteristic. Normally, the current which will flow thru an electron discharge device comprising an incandescent cathode and an anode enclosed in a highly evacuated envelope will, between certain limits, vary approximately as the 3/2 power of the applied voltage. In other words, the apparent resistance of such a device varies with the voltage applied to it. In some cases this characteristic is objectionable, as, for example, when such a device is included in a measuring circuit which comprises other resistance. In such a case the relation between current and voltage in the circuit will be a complex one and a calibration will be necessary to determine this relation. The present invention overcomes this disadvantage by constructing and arranging an electron discharge device in such a way that the current therethru

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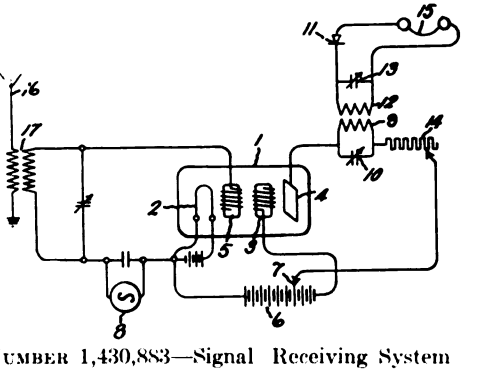
will vary directly as the applied voltage between certain well defined limits. A definite positive potential is impressed upon the grid of the tube which may be in the form of a separate battery or by connection of the grid with the positive end of the cathode. With this connection the apparent resistance between the filament and plate is constant over a definite working range of potential existing from a positive potential to a potential near the saturation potential.

1,430,808—Ray S. Hoyt, filed November 29, 1918, issued October 3, 1922. Assigned to American Telephone and Telegraph Company.

Two-Way Impedance Equalizer for Transformers. the equalizing impedance elements being so proportioned with reference to the external impedances and the self-inductances of the windings of the transformer, that if either external impedance be disconnected, the impedance of the remainder of the system will be substantially equal, over a considerable range of frequencies, to that of the disconnected external impedance.

1,430,883—B. Bradbury, filed March 23, 1921, issued October 3, 1922. Assigned to General Electric Company.



Number 1,430,883—Signal Receiving System

Signal Receiving System. This patent shows a new form of continuous wave receiver having an electron tube connected in a tuned receiving circuit functioning as a radio frequency amplifier, and a detector circuit inductively associated with the output circuit of the amplifier and tuned to the frequency of the incoming signals. The novelty of the receiver resides in the supplying of a continuous audio frequency current in the tuned cir-

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cuit associated with the radio frequency amplifier. Normally, there is no appreciable flow of audio frequency in the detector circuit, but upon the receipt of a radio frequency signaling current, the source of audio frequency energy at the receiver modulates the incoming energy and the modulated radio frequency signaling current is transmitted to the detector circuit where it is rectified, and the rectified current used to produce the desired audible response.

1,430,902—John Hays Hammond, Jr., filed May 10, 1918, renewed February 20, 1922, issued October 3, 1922.

LIGHT-SIGNAL SYSTEM, wherein lights may be carried by a mobile body such as a ship and a local circuit controlled to light the lamps upon receipt of sound waves.

1,431,219—George Crisson, filed May 20, 1919, issued October 10, 1922. Assigned to American Telephone and Telegraph Company.

ELECTRON TUBE REPEATER, with circuit connections for preventing interference between the individual tubes. The filaments of all of the tubes are connected in series in the heating circuit and connections are provided to prevent the flow of the variable component of the plate current of each tube in parts of the filament heating circuit other than the filament of each tube.

1,431,393—A. L. Golden, filed May 16, 1917, renewed August 9, 1922, issued October 10, 1922. Assigned to National Radio Company.

OSCILLATOR, comprising a spark gap construction for an oscillation circuit adapted for use with either radio telegraphy or telephony where smooth uniform radio frequency oscillations are required. The spark passes between the surfaces of two electrodes secured in a vertical position and submerged in distilled water. One of the electrodes is screw-threaded to permit micrometer adjustment of the distance between the electrodes which seldom exceeds three-thousandths of an inch (0.008 cm.) in this particular construction. The distilled water in which the electrodes are submerged is cooled by the circulation of cold water thru a coil submerged in the chamber surrounding the spark gap. The oscillation circuit is associated with the spark gap and a supply circuit connected therewith and an antenna radiating system linked with the oscillating circuit, the modulator being suitably associated with the antenna system.

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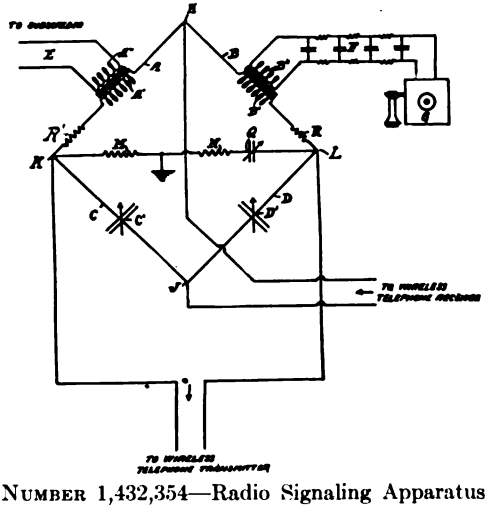
1,432,022—R. A. Heising, filed October 11, 1916, issued October 17, 1922. Assigned to Western Electric Company, Incorporated.

Circuit Connection on Electron Discharge Apparatus. This invention makes use of alternating current for heating the filaments of the electron tube used in a radio transmitter wherein the variations of potential differences between the grid and filament or the plate and filament are corrected to secure results approximating those obtained with direct current filament supply. In the circuits of this invention the alternating current is supplied from the secondary of a transformer and the connections from the anode and grid to the cathode are made to some point in the filament circuit which has a potential equal to the average potential of the filament, which in general is that of the middle point of the filament. When the connections are made in this way, the average voltage or difference of potential at any instance between different portions of the cathode and the grid and the anode due to the heating current will be zero.

1,432,354—W. H. Nottage, filed March 30, 1921, issued October 17, 1922. Assigned to Radio Corporation of America.



Number 1,432,354—Radio Signaling Apparatus

Radio Signaling Apparatus. The invention covered by this patent relates to a Wheatstone bridge circuit arranged for transferring connections from a line wire system to a radio system for transmission of signals coming in over a land line by

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radio and for transfer of signals received by radio to a telephone land line. In the Wheatstone bridge circuit a transformer winding is arranged in each of two adjacent arms. The secondary of these transformers may lead to land telephone lines which branch out to subscribers. The radio receiver is connected to two opposite junctions of the bridge and the radio transmitter is connected to the two other junctions of the bridge. With this arrangement signals coming in on the radio receiver will not affect the radio transmitter but will affect the land line so that they can be heard over that land line. Signals transmitted over the land line will not affect the radio receiver but will affect the radio transmitter by which they will be transmitted, because the latter is responsive to audible frequencies and the former is only affected by radio frequencies from the antenna.

1,432,384—W. W. Conners, filed June 12, 1919, issued October 17, 1922.

METHOD AND APPARATUS FOR INDICATING THE GEOGRAPHICAL LOCATION OR MOVEMENT OF BODIES. This patent shows an apparatus by which the movement of a tracing arm at a radio transmitting station produces a corresponding movement of an indicating arm upon a chart at a receiving station. For transmitting the geographical location of any point, the following principle is employed: A tracing arm is provided and arranged to move a switch arm over a set of contacts in such manner that a directive wave is propagated and rotatingly directed over a predetermined arc, starting a uniformly radiating wave at the beginning of the movement over the first wave over the arc, stopping the second wave at the conclusion of the movement of the first wave over the arc, receiving the second wave at the receiving station during its period of transmission, and noting the interval elapsing between the starting and stopping of the second wave in graduated units, receiving the first wave at the receiving station at the instance of its passage across the receiving station and noting the interval elapsing between the starting of the second wave and the passage of the first in the aforementioned units, reducing the ratio between the predetermined arc and the arc covered by the first wave to the instant of its reception at the receiving station from said intervals and thereby determining the angle between the beginning of the predetermined arc and the straight line passing thru the two stations.

1,432,411—J. H. Payne, Jr., filed April 21, 1921, issued October 17, 1922. Assigned to General Electric Company.

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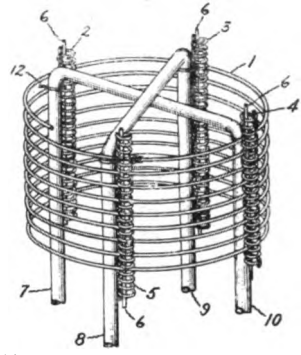
Fig. 2.



NUMBER 1,432,411—Electrode

ELECTRODE. This patent is directed to a rigid construction for a helical grid electrode for an electron tube. The electrode comprises a helix of relatively large diameter, the terms of which are supported at four points about the periphery of the helix by helices of comparatively small diameter mounted in a vertical position. The turns of the helix grid are interposed between every adjacent pair of turns of the small helices and a rod extends longitudinally thru each of the small helices locking the turns of the helix grid into position.

1,432,438—J. Bethenod, filed February 16, 1922, issued October 17, 1922.

RADIO TELEGRAPHIC COUPLING. This invention is directed to a coupling for transferring the radio frequency energy generated by an alternator to an antenna-ground system. The alternator of this invention has an armature winding divided into several sections not comprising any direct electric connection between them. A plurality of transformers each magnetically independent of the other have their primary windings inserted in series in a circuit alternately with the sections of the armature windings and the secondary windings of the transformers connected to the transmitting antenna and ground system.

1,432,455—Alfred N. Goldsmith, filed July 28, 1919, issued October 17, 1922. Assigned to Radio Corporation of America.

METHOD AND APPARATUS FOR RECEIVING SUSTAINED WAVE SIGNALS, without producing the beats at the receiver. The incoming sustained wave energy is modulated periodically or

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intermittently at a rate capable of producing an audio frequency cycle and an audible tone in the receiver. This modulation is effective by intermittently shielding the secondary from the primary coils acting as a transformer in the receiving circuits at a rate capable of modulating the incoming energy at an audible frequency, thereby varying the coupling and producing an audio frequency in the receiver. The apparatus may comprise a rotatable disk having a plurality of conducting projections movable thru the mutual field of the coils at a frequency corresponding to that of an audible tone.

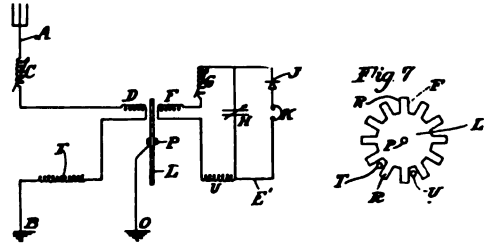
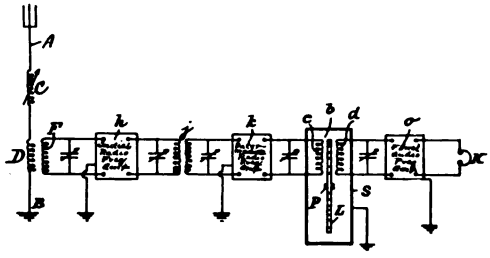


Fig. 6.



NUMBER 1,432,455—Method and Apparatus for Receiving Sustained Wave Signals

1,432,456—Alfred N. Goldsmith, filed July 29, 1919, issued October 17, 1922. Assigned to Radio Corporation of America.

METHOD AND APPARATUS FOR TRANSMITTING SUSTAINED WAVE SIGNALS, or tone transmission from a sustained wave generator. Sustained wave transmitters produce signals of constant amplitude radio frequency current, which signals are inaudible, or practically so, in a receiving system having the usual rectifying detector. This invention finds its application where it is desired to radiate a signal wave of such character that it is possible of reception and detection in the usual detector of a receiving set; for example, in a sustained wave transmitter on ship board, it may be desirable to transmit distress signals on a

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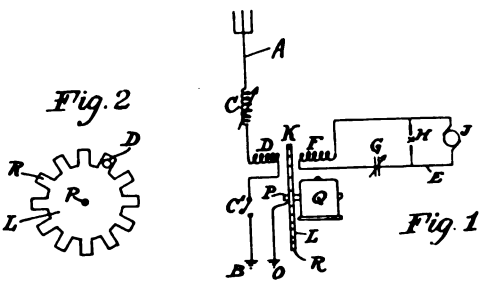
signal wave of a character to be received by the usual rectifying detector and not only by those receivers equipped for heterodyne or beat reception. The sustained wave radiation of an arc, alternator, oscillating electron tube, or other sustained wave transmitter, is periodically modulated by intermittently shielding the secondary from the primary coils forming the radio frequency transformer at a rate capable of producing radiation of tone character. This intermittent shielding is brought about by a rotating member having a plurality of conducting projections movable thru the mutual field of the inductively related coils at a frequency corresponding to that of an audible note.



NUMBER 1,432,456—Method and Apparatus for Transmitting Sustained Wave Signals

1,432,800—Louis Steinberger and Guy Hill, filed May 18, 1918, issued October 24, 1922.

INSULSTED SUPPORT FOR ELECTRICAL CONDUCTORS, such as flat metallic strip. The metal strip is molded at its center in insulating material.

1,432,863—Kenneth S. Johnson, filed July 1, 1918, issued October 24, 1922. Assigned to Western Electric Company, Incorporated.

TRANSMISSION SYSTEM. The patent shows a circuit connection of an electron tube amplifier with a line wherein the transformer coupling the line and the input circuit of the amplifier has an impedance connected to the primary side of the transformer closely approximating the effective impedance of the line.

1,432, 867—M. J. Kelly, filed November 15, 1919, issued October 24, 1922. Assigned to Western Electric Company, Incorporated.

ELECTRON DISCHARGE DEVICE AND METHOD OF MAKING THE SAME. The grid and plate of the electron tube of this inven-

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tion are provided with a black coating such as nickel oxide produced by oxidation in an electric furnace at a temperature of about 900° C. The object of the invention is to eliminate the "blocking" sometimes produced in electron tubes due partially to undesirable secondary emission from the grid and thermionic particles collected on the grid from filament emission, and also to increase the radiation characteristics of the electrodes to permit an increase in the power amplified and still maintain the temperature within safe limits. The nickel oxide coating on the grid practically eliminates secondary emission and thermionic emission due to the presence of particles of coating emitted from the filament. The coating having the characteristics of a black body radiator provides a means whereby the electrodes more efficiently radiate heat so that greater amounts of power may be supplied to them at a given temperature operation. Where the tube is to be used as a detector or an amplifier of minute currents, the coating is removed from the surface of the plate which lies in the path of the electron stream. The coating may be removed by action of a jet of hydrogen or other reducing agent while the face of the electrode is heated.

1,432,965—William L. Casper, filed September 3, 1919, issued October 24, 1922. Assigned to Western Electric Company, Incorporated.

Electric Circuits. This patent shows a filter circuit for use with electron tubes comprising a plurality of sections, each section having a branch in series with the line and a branch in shunt with the line. Each branch comprises an impedance element of such value that the phase angle of the series branch of each section equals the phase angle of the shunt branch of each section.

1,432, 992—J. O. Gargan, filed September 5, 1918, issued October 24, 1922. Assigned to Western Electric Company, Incorporated.

Vacuum Tube Socket. This patent shows a construction of support for carrying spare vacuum tubes in a radio set. The socket is not intended for connecting the terminals of the tube with external radio circuits, but is adapted to be secured in the corner of the cabinet containing the radio apparatus to carry a spare tube and prevent vibration or breakage thereof. The construction includes a resilient mounting on rubber strips and a spring-pressed member which engages the terminal pins

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of the tube and locks the tube by engagement with a bayonet slot co-operating with a pin in the side of the base of the tube.

1,433,070—W. W. Connors, filed June 6, 1919, issued October 24, 1922.

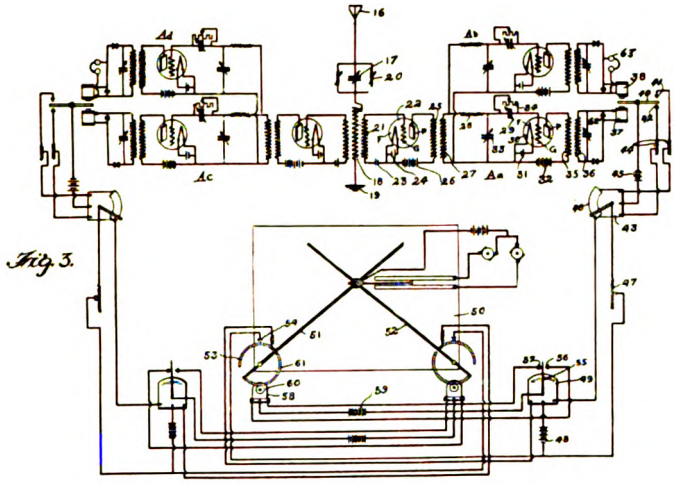

Fig. 3.

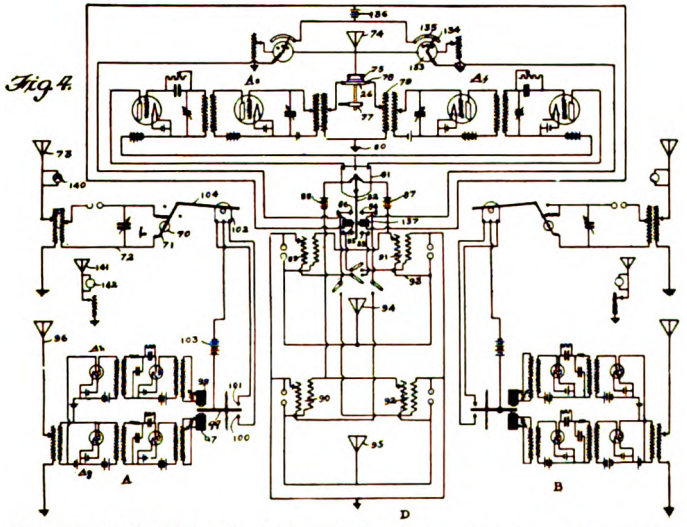

Fig. 4.

NUMBER 1,433,070—Method and Apparatus for Determining the Actual Location and Actual Movement of Bodies

METHOD AND APPARATUS FOR DETERMINING THE ACTUAL LOCATION AND ACTUAL MOVEMENT OF BODIES. This patent shows an arrangement of radio transmitting stations Figure 4,

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and a receiving station, Figure 3, with apparatus at the receiving station whereby a plurality of transmitting stations may operate to control the apparatus at the receiving station for performing such functions as reproducing graphically geographical representations and an altitude representation of an object such as a map or topographic survey existing at the transmitting stations. The receiving apparatus includes a similitude board arranged to represent the field of movement of a motile body. An indicator is arranged to be moved over the board in accordance with signals received from transmitting stations.

1,433,224. J. Parkin, Jr., filed March 29, 1920, issued October 24, 1922.

VARIABLE CONDENSER construction comprising a container for a quantity of mercury which may be rotated, the body of mercury remaining stationary by reason of its own specific gravity while a plate carried in the wall of the container and separated from the mercury by dielectric is moved relatively to the body of mercury. The container has the shape of a pair of disks separated from each other with the mercury between the disks in the lower half of the container; the opposite plate of the condenser is carried by the container separated from the mercury body by a dielectric.

The following digests should be considered as included with digests appearing in previous issues of the PROCEEDINGS.

1,422,447—Le Roy Wilson Kalsay, filed February 8, 1921, issued July 11, 1922. Assigned to Western Electric, Company, Incorporated.

SWITCHING KEY, comprising an oscillatory member pivotally mounted within a rectangular frame. The member is arranged to be rocked in single plane to connect contacts carried by the member with stationary contacts mounted on the frame.

1,422,837—Irving B. Crandall, filed October 13, 1917, issued July 18, 1922. Assigned to Western Electric Company, Incorporated.

CONNECTING TRANSMITTERS TO VACUUM TUBE AMPLIFIERS. This patent shows a circuit connection between a telephone transmitter and an electron tube amplifier in which the "B" battery is employed to supply both the plate potential and the transmitter circuit.

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1,426,516—Louis Steinberger, filed April 29, 1918, issued August 22, 1922.

INSULATOR of the molded interlocked strain member type. The invention resides in the construction of the imbedded portions of the strain members. Each strain member is provided with imbedded arm and ring portions increasing the tensile strength of the insulator.

1,426,754—Robert C. Mathes, filed October 23, 1916, issued August 22, 1922. Assigned to Western Electric Company, Incorporated.

CIRCUITS FOR ELECTRON DISCHARGE DEVICES, in which a resistance is connected in the input circuit of a tube and a battery related therewith for bringing the grid to a different potential than the filament and arranged so that gradual fluctuations in the strength of the plate battery will be compensated by fluctuations in the grid battery.

1,426,755—Robert C. Mathes, filed May 9, 1919, issued August 22, 1922. Assigned to Western Electric Company, Incorporated.

VACUUM TUBE CIRCUITS AND METHODS OF OPERATING THEM. A plurality of electron tubes are connected in tandem in such manner that the input circuit of one of the tubes includes the filament electrode of the succeeding tube.

1,426,788—Louis Steinberger, filed November 26, 1918, issued August 22, 1922.

INSULATOR STRAIN MEMBER for a molded insulator. The strain members are interlocked and imbedded in the insulator. The invention resides in the ring shape bridge construction formed in the leg portions of the strain members for increasing the tensile strength of the insulator.

1,426,789—Louis Steinberger, filed January 28, 1922, issued August 22, 1922.

INSULATOR of molded material having interlocked strain members imbedded therein. The imbedded portions of each of the strain members are in the form of rings circular in cross section.

1,426,807—Harold D. Arnold and John P. Minton, filed Novem-

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ber 12, 1917, issued August 22, 1922. Assigned to Western Electric Company, Incorporated.

METHOD AND SYSTEM FOR TESTING TRANSMITTERS OR RECEIVERS for telephone systems. A generator such as a vacuum tube oscillator is arranged to supply a current continuously variable in frequency in a regular manner. The current is amplified and operates the receiver acoustically coupled with the transmitter under test. The operation of the transmitter can be observed from meters connected in the transmitter circuit.

LIST OF RADIO TRADE MARKS PUBLISHED BY PATENT OFFICE PRIOR TO REGISTRATION

The numbers given are serial numbers of pending applications:

161,016—"TELERADIO" for radio and electrical equipment. Teleradio Engineering Corporation, New York, N. Y. Claims use since March 11, 1922. Published August 29, 1922.

161,679—"THE RADIO BOYS' SERIES"—series of books published periodically. Grosset & Dunlap, Incorporated, New York, N. Y. Claims use since March 1, 1922. Published August 29, 1922.

164,214—"RADION"—insulation material and horns for radio loud speakers. American Hard Rubber Company, Hempstead and New York, N. Y. Claims use since April 14, 1922. Published August 29, 1922.

163,112—"AMPERITE"—filament control adjuster. Radiall Company, New York, N. Y. Claims use since March 15, 1922. Published August 29, 1922.

163,304—"AUDIOLA" for radio apparatus. Audiola Radio Company, Chicago, Illinois. Claims use since March 31, 1922. Published August 29, 1922.

164,454—"RA-FONE" for radio receiving sets. Ra-Tone Electric Company, Detroit, Michigan. Claims use since early part of March, 1922. Published August 29, 1922.

162,601—"ATLANTIC WAVES IN EVERY HOME" for radio apparatus. Atlantic Instrument Company, Incorporated, New York, N. Y. Claims use since on or about January 2, 1922. Published September 26, 1922.

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163,091—"LALLEY RADIO" forming two hemispheres, one in black and one in red. Radio receiving sets. Lalley Radio Corporation, Detroit, Michigan. Claims use since April 17, 1922. Published September 26, 1922.

163,421—"AERIOLA GRAND" for radio apparatus. Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pennsylvania. Claims use since December 23, 1921. Published September 26, 1922.

163,508—"ALADDIN MULTITONE COMPLETE CRYSTAL RECEIVER" in ornamental design. Philip E. Edelman, New York, N. Y. Claims use since December 22, 1921. Published September 26, 1922.

163,555—"MAXOLOUD" for radio apparatus. Paul F. Weiss, doing business as Radio Improvement Company, not incorporated, Chicago, Illinois. Claims use since March 29, 1922. Published September 26, 1922.

164,321—Symbol of antenna and ground with letters "H R C" for radio receiving apparatus. Heslar Radio Corporation, Indianapolis, Indiana. Claims use since April 25, 1922. Published September 26, 1922.

164,439—"JRH RADIO" arranged in triangle, for radio receiving apparatus. J. Roy Hunt, Incorporated, Long Island City, N. Y. Claims use since April 15, 1922. Published September 26, 1922.

164,444—"MORADIO" for radio apparatus. Moreland Sales Corporation, Newark, New Jersey. Claims use since March 15, 1922. Published September 26, 1922.

164,598—"OIDAR—THE VOICE HEARD ROUND THE WORLD" arranged in the form of a globe. For radio apparatus. Ludwig Hommel and Company, Pittsburgh, Pennsylvania. Claims use since April 24, 1922. Published September 26, 1922.

164,604—"AEROVOX" for radio apparatus. The Radiola Wireless Corporation, New York, N. Y. Claims use since April 1, 1922. Published September 26, 1922.

164,728—"AMPLITONE" antenna wire. W. C. Shinn Manufacturing Company, Niles, Michigan and Chicago, Illinois. Claims use since April 25, 1922. Published September 26, 1922.

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161,941—"RADIO DIGEST"—weekly publication. Earl C. Rayner, Chicago, Illinois. Claims use since April 4, 1922. Published October 3, 1922.

163,412—"PINK-A-TONE—DETECTOR OF THE AIR" arranged ornamentally. Radio receiving sets. Pinkerton Electric Equipment Company, New York, N. Y. Claims use since on or about April 10, 1922. Published October 10, 1922.

163,528—"THE STANDARD RADIO GUIDE"—radio manual issued at intervals. Modern Publishing Company, New York, N. Y. Claims use since April 20, 1922. Published October 10, 1922.

162,615—"EDELMAN'S MULTITONE" for radio receiving sets. Philip E. Edelman, New York, N. Y. Claims use since August 1, 1921. Published October 17, 1922.

162,805—"ZENITH" in wavelike design, for radio apparatus. Chicago Radio Laboratory, Chicago, Illinois. Claims use since about October, 1918. Published October 17, 1922.

163,425—"GREAT RADIO VOICE—THOROPHONE—(THUNDERPHONE)" arranged in ornamental design; for radio receiving apparatus. Winkler-Reichmann Company, Chicago, Illinois. Claims use since April 20, 1922. Published October 17, 1922.

163,864—"RADIO REVIEW"—monthly publications. Experimenter Publishing Company, Incorporated, New York, N. Y. Claims use since January 20, 1922. Published October 17, 1922.

164,080—"RADIO REMCO PRODUCTS" arranged in ornamental design; for radio apparatus. Alfred J. Steinberger, doing business as Radio Equipment and Manufacturing Company, Brooklyn, New York. Claims use since on or about February 1, 1922. Published October 17, 1922.

164,864—"THE RADIO BOYS"—printed books published in series. A. L. Burt Company, New York, N. Y. Claims use since April 21, 1922. Published October 17, 1922.

165,250—"THE WORLD'S VOICE" arranged in ornamental design. For radio receiving apparatus. Victor Radio Corporation, New York, N. Y. Claims use since May 15, 1922. Published October 17, 1922.

165,374—"RADIONELLE" for radio receiving apparatus. A. H.

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Grebe and Company, Incorporated, Richmond Hill, N. Y. Claims use since on or about March 1, 1922. Published October 17, 1922.

165,604—" 'STATI-TUBE'—ROCHESTER, N. Y." for Radio detector, amplifier, and transmitter tubes. Radio Stati-Tube Manufacturing Company, Incorporated, Rochester, N. Y. Claims use since May, 1921. Published October 17, 1922.

165,819—"ROYALFONE—KING OF ALL" for head telephone receivers. Royal Electrical Laboratories, Newark, New Jersey. Claims use since March 1, 1922. Published October 17, 1922.

165,887—"RAD-WIN-CO" in ornamental design; for radio apparatus. Radio Winding Corporation, New York, N. Y. Claims use since May 15, 1922. Published October 17, 1922.

166,040—"RADAK" for radio equipment. Clapp-Eastham Company, Cambridge, Massachusetts. Claims use since June 3, 1922. Published October 17, 1922.

166,490—"X-RAD" for radio apparatus. X-Rad Corporation, New York, N. Y. Claims use since on or about May 20, 1922. Published October 17, 1922.

167,784—"RICO" for radio telephones. Radio Industries Corporation, New York, N. Y. Claims use since June 10, 1922. Published October 17, 1922.

167,882—"CONQUEROR" arranged in ornamental design; for radio receiving apparatus. Lewis and De Roy Radio Corporation, New York, N. Y. Claims use since April 1, 1922. Published October 17, 1922.

167,962—"AERIOTRON" for electron tubes. Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pennsylvania. Claims use since December 10, 1921. Published October 17, 1922.

168,496—"ERECTO-RADIO" for radio receiving equipment. Stephenson Radio Company, Indianapolis, Indiana. Claims use since June 30, 1922. Published October 17, 1922.

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PROCEEDINGS of The Institute of Radio Engineers

EDITED BY
ALFRED N. GOLDSMITH, Ph.D.

PUBLISHED EVERY TWO MONTHS BY
THE INSTITUTE OF RADIO ENGINEERS
THE COLLEGE OF THE CITY OF NEW YORK
140th Street and Convent Avenue, New York, N. Y

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Model	Cap. Mfd.	Volts Eff.	Amps.	Meters	Cycles	Name
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UC 1015	.0003 .0004 .0005	7500	4 Tel. Load	200		Series—Antenna
UC 1800	.02	15000	0.1		50–1000	Filter
UC 1801	.002	15000	5	3000		Radio Bipass
UC 1802	.0004	10000	2			Grid
UC 1803	.000025	10000	1	200		Ant. Coupling
UC 1804	.002	15000	9	3000		Dummy Antenna 28 Amp. at 300M
UC 1805	.001	5000	.5	2500		Grid
UC 1806	.002	6000	2	200		Plate Bipass
UC 1807	.00002	50000	2	600		Ant. Coupling
UC 1808	.0001	4000	3	450		Trap
UC 1809	.001	8000	15	450		Series
UC 1810	.0001–.00001 Ten Tap	15000	1	300		Grid Coupling
UC 1812	.25		2	200		Amplifier
UC 1821	.02		.02		800	Radio Bipass
UC 1822	.004		10	1000		Spark Primary
UC 1830	1.0		1		800	Radio Bipass
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UC 1840	.0005		10 Tel. Load		600	Series Antenna

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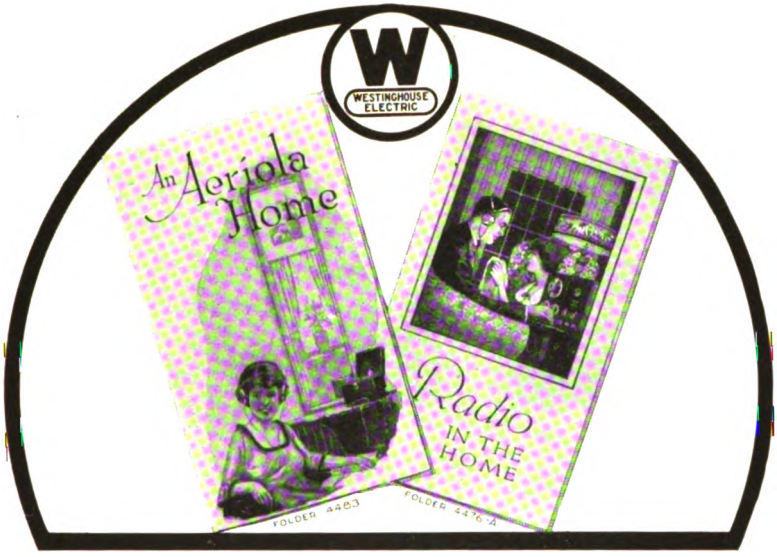

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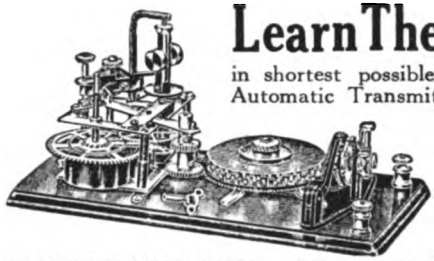

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(1) In trans-oceanic communication, the routing designation *"Via RCA"* has come to mean that the sender of a radio message wishes to avail himself of the Radio Corporation of America's unexcelled service—a service that insures accuracy, speed and economy.

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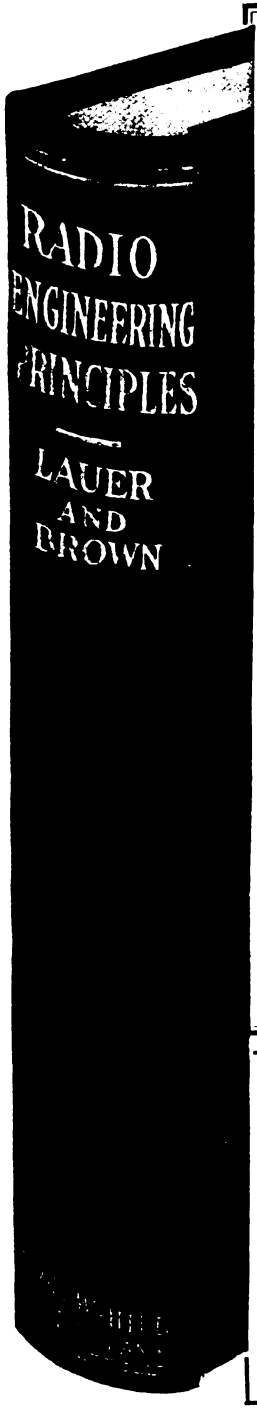

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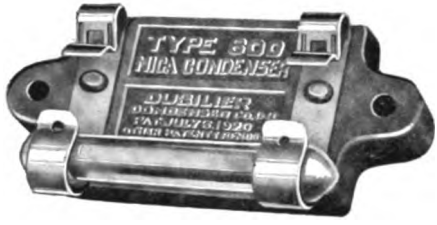

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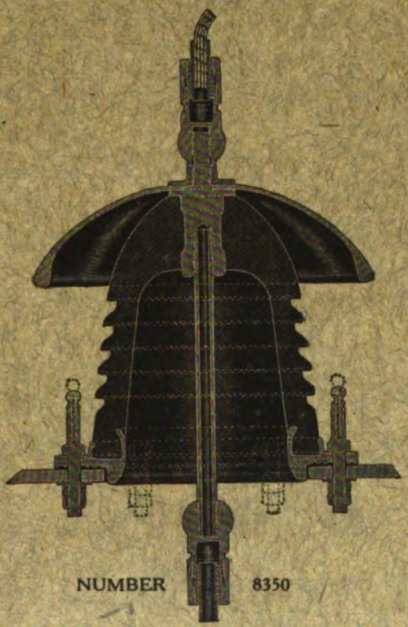

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VOLUME 10 DECEMBER, 1922 NUMBER 6

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ALFRED N. GOLDSMITH, Ph.D.

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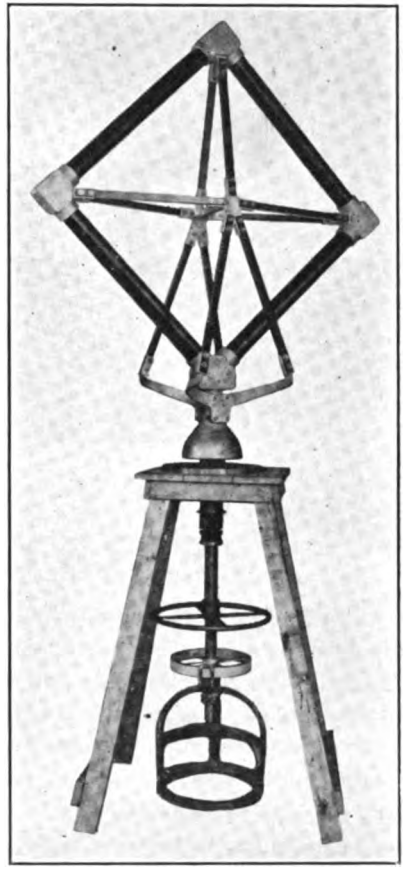
Manufactured Under the Pickard Loop Patents



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BOSTON, MASS. *Established 1907* **U. S. A.**

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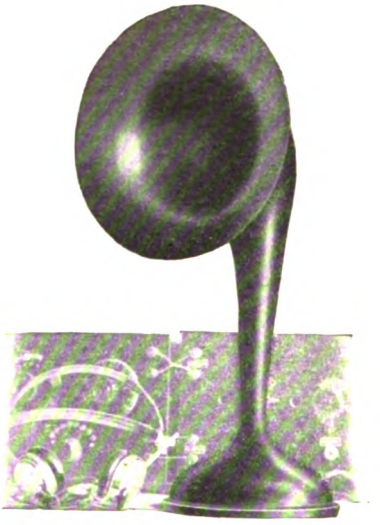

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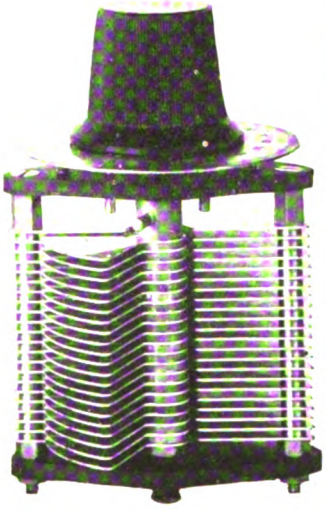

You can drop a Sleeper Condenser on the floor, throw it across the room and give it rough treatment that no other condenser will stand because it has no lead supports and no flimsy zinc plates. The smooth running steel shaft is copper plated to prevent rusting and reduce the resistance. In a horizontal position the plates stay put because of the adjustable friction take-up on the bearing.

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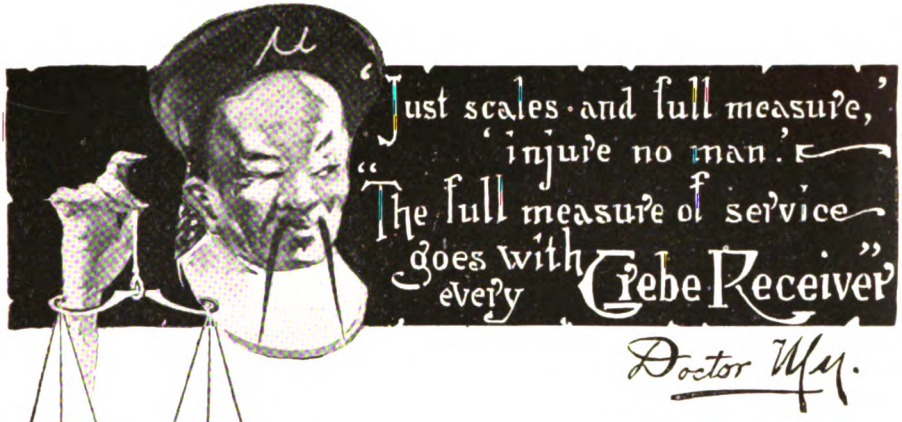

ANYONE who knows radio will tell you how well the Grebe CR-5 performs on the daily concerts, lectures, etc., in the air.

Two simple tuning adjustments are used. Tiresome adjustments, unpleasant interruptions are unnecessary with the Grebe CR-5. Its range, 150—3000 metres.

Ten years experience in satisfying a critical radio public has taught us how to build it for your year-round enjoyment.

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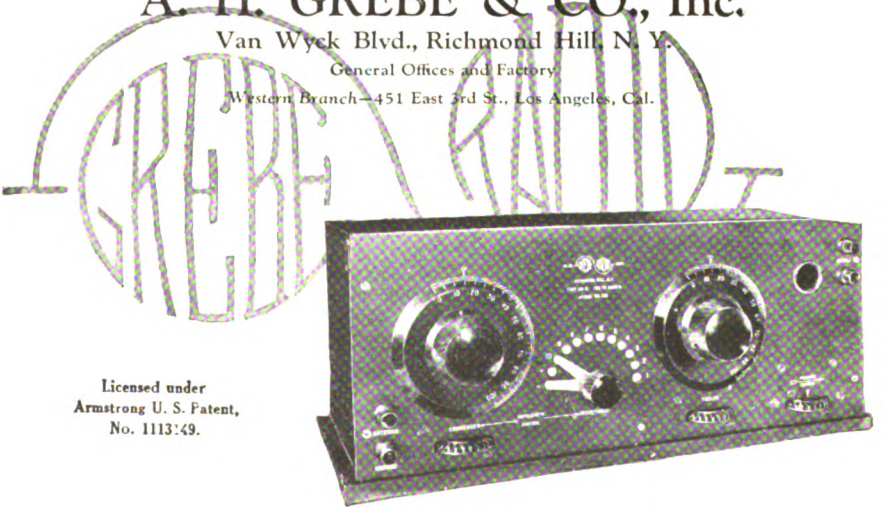

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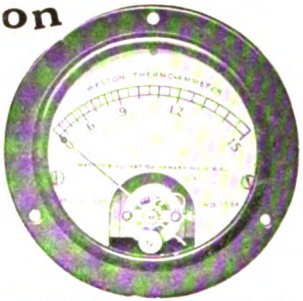

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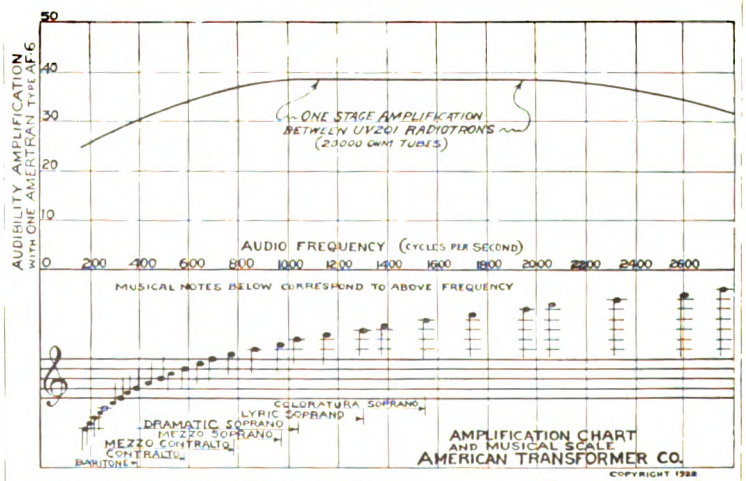

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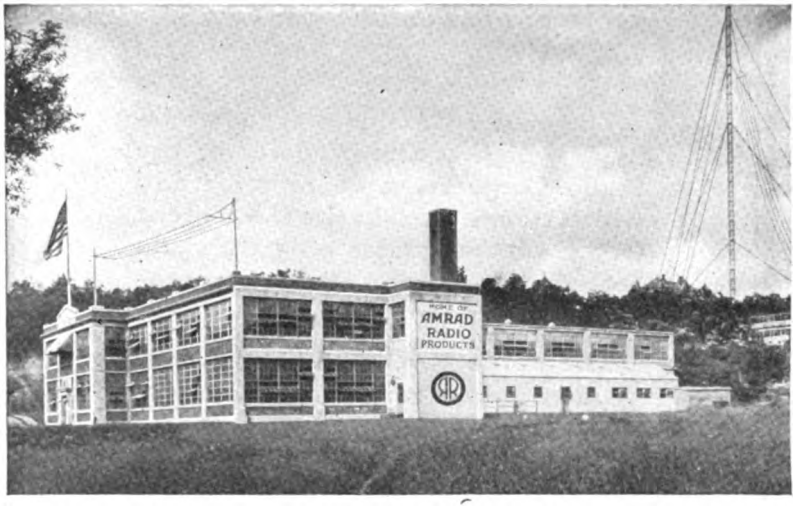

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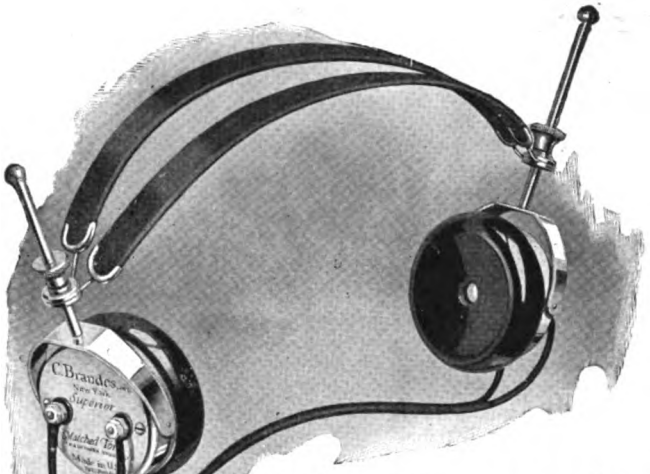

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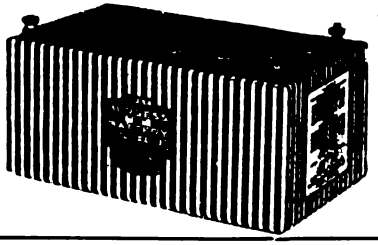

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The circuit is a combination of radio and audio frequency. The signals are first passed through the three tubes at radio frequency. The amplified radio frequency signal is then rectified in a crystal detector. The rectified signal is then "reflexed" through the last two tubes at audio frequency, and the signal is conducted to the head-phones or the loud speaker. The result is 5 stages of amplification with three tubes.

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This set consists of a ¼-inch grained Bakelite panel and a solid mahogany cabinet, with Bakelite moulded knobs and dials. The metal parts are nickel plated, except the screw-heads which are baked black enamel. The tubes are mounted vertically on an inside shelf, and peep holes are provided for observation of the tubes in operation. Radio frequency transformers are plugged into receptacles on same shelf with tubes. All battery connections are made through the rear. The Filament rheostat controls all three tubes. The top of the cabinet is hinged to allow easy accessibility to interior, the hinges and catch being sunken. A bezel-ringed hole is provided in this hinged cover to enable the loop to be plugged into telephone jack on shelf. Plugging in the loop automatically disconnects the vario-coupler, which is used when reception is by means of outside antenna. Regulation of signal intensity is accomplished by means of an A Battery Potentiometer located at right center of panel. The stops of the vario-coupler condenser are arranged under the dials so that no strain can be put on the rotating units. Sets are wired with No. 14 hard-drawn copper wire nickel plated standard bus type.

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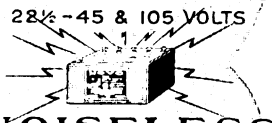

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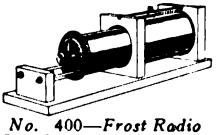

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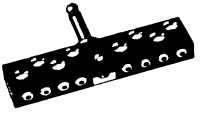

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